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CCM-82-06

STRAIN ENERGY RELEASE RATE DETERMINATION OF STRESS INTENSITY FACTORS BY FINITE ELEMENT METHODS

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--                        ***DTIC DOES NOT HAVE THIS ITEM***
-- 1 -  AD NUMBER: D437149
-- 6 -  UNCLASSIFIED TITLE:     STRAIN ENERGY RELEASE RATE DETERMINATION OF
--      STRESS INTENSITY FACTORS BY FINITE ELEMENT METHODS,
--10 -  PERSONAL AUTHORS: WALSH,R. M. , JR.;
--11 -  REPORT DATE:       DEC    , 1982
--12 -  PAGINATION:     134P
--14 -  REPORT NUMBER:     CCM-82-06
--20 -  REPORT CLASSIFICATION:  UNCLASSIFIED
--21 -  SUPPLEMENTARY NOTE:     MS. THESIS SUBMITTED TO UNIVERSITY OF
--      DELAWARE.
--22 -  LIMITATIONS (ALPHA):    APPROVED FOR PUBLIC RELEASE; DISTRIBUTION
--      UNLIMITED. AVAILABILITY: CENTER FOR COMPOSITE MATERIALS, UNIVERSITY
--      OF DELAWARE, NEWARK, DE. 19711.
--33 -  LIMITATION CODES:  1  24
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Sponsored by the

National Aeronautics and Space Administration
Langley Research Center
Langley, Virginia

Contract Number NSG 1304

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Mechanical and Aerospace Engineering.

December 1982

ABSTRACT

The determination of the Mode I stress intensity factors for selected crack configurations, using finite element methods and energy release rate principles, is the subject of this study. The crack configurations which were investigated were the double edge crack, the single edge crack, and the center crack. The method of analysis utilized was the "Stiffness Derivative Method" [7]. This approach relates the change in strain energy resulting from crack advancement, to the change in the stiffness matrix of the structure containing the crack. The results indicated that through mesh optimization and proper control of certain parameters including the crack advance increment, the crack tip element contour size, and mesh refinement, an accurate solution can be calculated with a relatively coarse finite element mesh consisting entirely of contemporary elements. The numerically generated solutions are compared with analytical solutions with the results within 0.001 percent of each other for the double edge crack, 0.858 percent for the single edge crack, and 2.021 percent for the center crack.

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NOMENCLATURE

Symbol	Meaning
a	Crack half-length
[B]	Strain-displacement proportionality matrix
b	Plate half-width
[D]	Stress-strain proportionality matrix
E	Young's modulus
e	Primary subscript designator
F	Work done by external forces
G	Energy release rate
K_I, K_{II}, K_{III}	Stress intensity factor (Modes I, II, III)
[K]	Overall stiffness matrix
[k]	Element stiffness matrix
$\{L\}$	Load vector
ℓ	Element superscript designator
o	Secondary subscript designator
P	Total potential energy
r	Radial distance from crack tip
S	Thermal and residual effect energy term
u,v,w	x, y and z displacements

$\{u\}$	Nodal displacement vector
U	Elastic strain energy
W	Energy available for crack growth
σ	Normal stress component
$\{\sigma\}$	Stress vector
τ	Shear stress component
$\{\varepsilon\}$	Strain vector
ν	Poisson's ratio
θ	Angle of inclination from crack line
ϕ	Dummy integration variable
δ	Crack tip closure increment
Ω	Strain energy density
Γ_o	Crack tip inner element contour
Γ_1	Crack tip outer element contour

INTRODUCTION

The initiation and growth of cracks in a material as a result of pre-existing flaws has been an extremely important phenomenon in the historical development and use of materials. With the advent of today's high-strength materials and their subsequent application in many sectors of our society, a more definitive understanding of the fracture phenomenon is essential if these materials are to be utilized safely and most effectively. This need is readily apparent in many of the current high-technology design applications which employ advanced composites with specified material properties and a high strength-to-weight ratio. As a result of such advanced application it is no longer practical in design to overspecify the material with a sufficiently large factor of safety to compensate for any probable defects. Instead, the designer must work within increasingly smaller safety factors while accounting for the inherent defects present in the material resulting from the fabrication process as well as from damage incurred subsequent to fabrication.

To define the stress field around a specific crack configuration, it is necessary to determine the stress intensity factor. With that determined, one is then able to predict the crack

growth and the time to fracture which are the important factors related to any defect [1]. Of the three crack mode stress intensity factors, the Mode I factor, K_I, is generally the most important, and is the one which is evaluated in this report [1].

The modeling of the crack configurations and determination of the respective stress intensity factors is accomplished by means of numerical methods; specifically the finite element method. Some previous studies using finite elements to solve this problem have developed special "singularity elements" for use at the crack tip [2-4]. Such elements are specifically designed to incorporate the elastic stress singularity at the crack tip. The method is classified as one of the direct methods. While reasonable accuracy was obtained by these means, it is more desirable to use conventional elements in view of their universal availability and less complicated incorporation into the overall mesh.

In selecting a method of analysis as a basis for this study, a number of factors serve as guidelines. First, the model must use conventional elements for reasons previously discussed. In addition, error based on comparisons with analytical solutions should initially be within 5 percent to warrant further investigation and refinement. The term "error", as used in this report, is defined as:

$$\text{Percent Error} = \left[\frac{(\text{Analytical solution})-(\text{Numerical solution})}{(\text{Analytical solution})}\right] \text{X}100$$

The third guideline is that the mesh must be optimized so as to result in a relatively coarse mesh configuration which is still sufficiently accurate. The mesh optimization is important so as to minimize computing time and thereby lay the groundwork for the implementation of the method in solving the more extensive three-dimensional problems related to interlaminar flaws in composite laminates. Based on the specified criteria, a number of the indirect methods involving energy methods have been found to be viable choices [5-7]. Of those, the "Stiffness Derivative Method" used by Parks [7] has been chosen for this study.

The "Stiffness Derivative Method" is based on evaluating the energy release due to crack extension as it relates to the corresponding change in the stiffness. It requires the results of only one crack advancement to compute the solution.

In this current research endeavor, the method is used to evaluate the Mode I stress intensity factors of three two-dimensional crack configurations. Those configurations include the single edge crack, the double edge crack, and the center crack. In all cases, mesh optimization techniques [8] are employed, and numerical solutions generated which are compared to their corresponding analytical solutions.

CHAPTER 1: THEORETICAL FORMULATION

1.1 The Stress Intensity Factor

The characterization of the deformation of a crack can be separated into three distinct modes of local deformation as shown in Figure 1. In each case, the crack deformation is the result of a different state of stress being present in the body. The opening mode (Mode I) is the result of an in-plane normal stress on the crack. The sliding mode (Mode II) also involves an in-plane stress, but in this case it is a shear stress. By contrast the presence of an out-of-plane shear stress causes the tearing mode (Mode III). Very often, the stress state near the crack tip is actually a mixed mode situation with a combined effect of the three modes to varying degrees. Of the three modes, Mode I has been found to be the predominant deformation mode, and is the one which is concentrated on in this study [1].

In the case of an infinite plate in the x-y plane with a through crack and an in-plane stress state normal to the crack (Mode I), the components of the elastic stress field of an element dxdy at a distance r from the crack tip and an angle θ from the crack line, as shown in Figure 2, are found to be (omitting higher

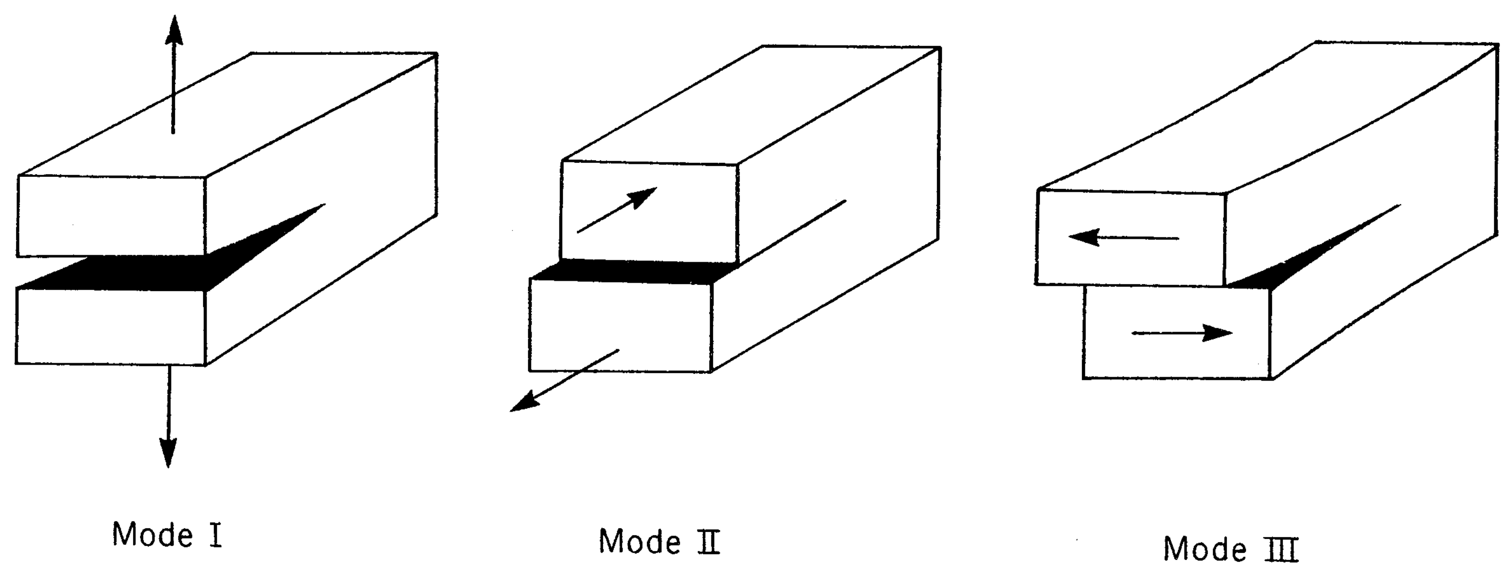

Figure 1. Crack Deformation Modes

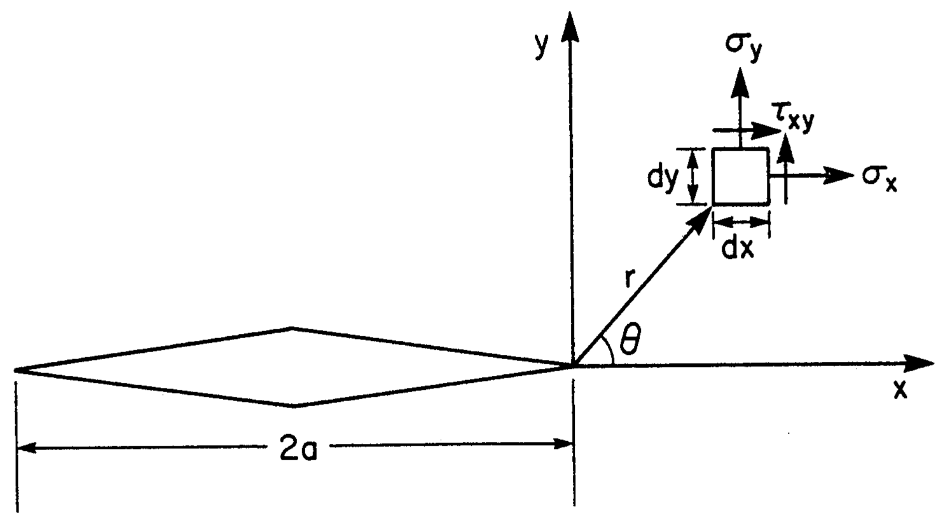

Figure 2. Crack Tip Stress Field Components and Coordinates

order terms) [1]:

$$\sigma_x = \sigma(a/2r)^{1/2} \cos(\theta/2)[1 - \sin(\theta/2)\sin(3\theta/2)] \quad (1.1)$$

$$\sigma_y = \sigma(a/2r)^{1/2} \cos(\theta/2)[1 + \sin(\theta/2)\sin(3\theta/2)] \quad (1.2)$$

$$\tau_{xy} = \sigma(a/2r)^{1/2} \sin(\theta/2)\cos(\theta/2)\cos(3\theta/2) \quad (1.3)$$

$$\sigma_z = 0 \qquad \text{(plane stress)} \quad (1.4)$$

$$\sigma_z = \nu(\sigma_x + \sigma_y) \qquad \text{(plane strain)} \quad (1.5)$$

In these expressions, a is the half-crack length. These equations can generally be expressed as [1]:

$$\sigma_{ij} = \frac{K_I}{(2\pi r)^{1/2}} f_{ij}(\theta) \quad (1.6)$$

where

$$K_I = \sigma(\pi a)^{1/2} \quad (1.7)$$

K_I is called the Mode I stress intensity factor.

The Mode I elastic stress field of the element dxdy and the Cartesian displacements (u,v,w) can be expressed as [9]:

$$\sigma_x = \frac{K_I}{(2\pi r)^{1/2}} \cos(\theta/2)[1 - \sin(\theta/2)\sin(3\theta/2)] \quad (1.8)$$

$$\sigma_y = \frac{K_I}{(2\pi r)^{1/2}} \cos(\theta/2)[1 + \sin(\theta/2)\sin(3\theta/2)] \tag{1.9}$$

$$\tau_{xy} = \frac{K_I}{(2\pi r)^{1/2}} \sin(\theta/2)\cos(\theta/2)\cos(3\theta/2) \tag{1.10}$$

For plane strain:

$$\sigma_z = \nu(\sigma_x + \sigma_y) \tag{1.11}$$

$$\tau_{xz} = \tau_{yz} = 0 \tag{1.12}$$

$$u = \frac{2K_I(1+\nu)}{E} (r/2\pi)^{1/2} \cos(\theta/2)[1 - 2\nu + \sin^2(\theta/2)] \tag{1.13}$$

$$v = \frac{2K_I(1+\nu)}{E} (r/2\pi)^{1/2} \sin(\theta/2)[2 - 2\nu - \cos^2(\theta/2)] \tag{1.14}$$

$$w = 0 \tag{1.15}$$

Similarly, the Mode II elastic stress field and displacements are expressed as [9]:

$$\sigma_x = \frac{-K_{II}}{(2\pi r)^{1/2}} \sin(\theta/2)[2 + \cos(\theta/2)\cos(3\theta/2)] \tag{1.16}$$

$$\sigma_y = \frac{-K_{II}}{(2\pi r)^{1/2}} \sin(\theta/2)\cos(\theta/2)\cos(3\theta/2) \tag{1.17}$$

$$\tau_{xy} = \frac{K_{II}}{(2\pi r)^{1/2}} \cos(\theta/2)[1 - \sin(\theta/2)\sin(3\theta/2)] \tag{1.18}$$

For plane strain:

$$\sigma_z = \nu(\sigma_x + \sigma_y) \tag{1.19}$$

$$\tau_{xy} = \tau_{yz} = 0 \tag{1.20}$$

$$u = \frac{2K_{II}(1+\nu)}{E} (r/2\pi)^{1/2} \sin(\theta/2)[2 - 2\nu + \cos^2(\theta/2)] \tag{1.21}$$

$$v = \frac{2K_{II}(1+\nu)}{E}(r/2\pi)^{1/2} \cos(\theta/2)[-1 + 2\nu + \sin^2(\theta/2)] \tag{1.22}$$

$$w = 0 \tag{1.23}$$

The Mode III elastic stress field and displacements are expressed as [9]:

$$\tau_{xz} = \frac{-K_{III}}{(2\pi r)^{1/2}}\sin(\theta/2) \tag{1.24}$$

$$\tau_{yz} = \frac{K_{III}}{(2\pi r)^{1/2}}\cos(\theta/2) \tag{1.25}$$

$$\sigma_x = \sigma_y = \sigma_z = \tau_{xy} = 0 \tag{1.26}$$

$$w = \frac{2K_{III}(1+\nu)}{E} (2r/\pi)^{1/2} \sin(\theta/2) \tag{1.27}$$

$$u = v = 0 \tag{1.28}$$

In these equations, K_{II} and K_{III} are the Mode II and Mode III stress intensity factors respectively.

The expression for K_I in equation (1.7) is that corresponding to the case of a crack in an infinite plate. In actual

applications with plates of finite width, the expression becomes less accurate as the ratio of the crack half-length to plate half-width, (a/b), increases. To account for such effects, the stress intensity factor is expressed as [1]:

$$K_I = \sigma(\pi a)^{1/2} f(a/b) \tag{1.29}$$

in which the function f(a/b) is a function of the crack half-length, a, and the plate half-width, b.

If the applied stress, σ, on the plate with the crack is increased, it will eventually reach a point at which time the plate will fracture. The applied stress at this point is the failure stress, σ_c. The corresponding stress intensity factor is the critical stress intensity factor or the fracture toughness which is expressed as [1]:

$$K_{I_c} = \sigma_c (\pi a)^{1/2} f(a/b) \tag{1.30}$$

Physically, the fracture toughness is an indication of the resistance of a material containing a crack to fracture. With this factor known for a certain material, it is possible to determine the maximum allowable crack size without the onset of fracture for a given stress level. Conversely, the fracture strength of the material for a given crack size can also be calculated. The results of equation (1.30) are valid when a condition

of plane strain exists. If a plane stress condition is present, then the critical stress intensity factor is dependent upon the thickness of the plate also [1]. The importance of knowing the stress intensity factor is quite apparent since with that information, one can determine the crack growth behavior as well as the point at which a material will fracture.

1.2 The Griffith Energy Criterion

For an infinite plate with a through crack of half-length, a, and normal in-plane stress, σ, Griffith showed that in order for the crack to propagate, the following conditions must exist [1]:

$$\frac{dW}{da} = \frac{d}{da}(F - U) \tag{1.31}$$

In this equation, W is the energy available for crack growth, F is the work done by external forces, and U is elastic strain energy of the plate. In essence, the equation indicates that crack propagation will occur when conditions are such that the energy released as a result of the crack extension is equal to the energy required for the crack growth.

If the loading of the plate is such that the ends are

fixed, then the external forces do no work. In this situation, the energy for crack growth comes from a release of elastic energy, resulting in a decrease in the elastic energy content of the plate. If the ends of the plate are free, then the external forces do work in this case. The result of the input work energy is an increase in the elastic energy content of the plate, as well as energy being made available for crack growth.

The concept of the energy release rate, as developed by Irwin [10], can be used to relate the stress intensity factor to the Griffith criterion for crack growth. Physically, the energy release rate, G, is the rate at which energy is made available for crack propagation, with the energy originating from a release of elastic energy of the material, or from work done on the body by external forces, or some combination of both. The energy release rate is expressed by Irwin in terms of the crack closure integral [9]:

$$G = \lim_{\delta \to 0} \frac{2}{\delta} \int_0^{\delta} \left[\frac{\sigma_y v}{2} + \frac{\tau_{xy} u}{2} + \frac{\tau_{yz} w}{2} \right] dx \qquad (1.32)$$

This is an expression of the rate of change of work energy with respect to crack length as a result of closing the crack tip a distance δ, as in Figure 3. The stresses and displacements are those of the crack surface which is pulled closed. In equation (1.32), the factor of 2 is present because two crack faces are

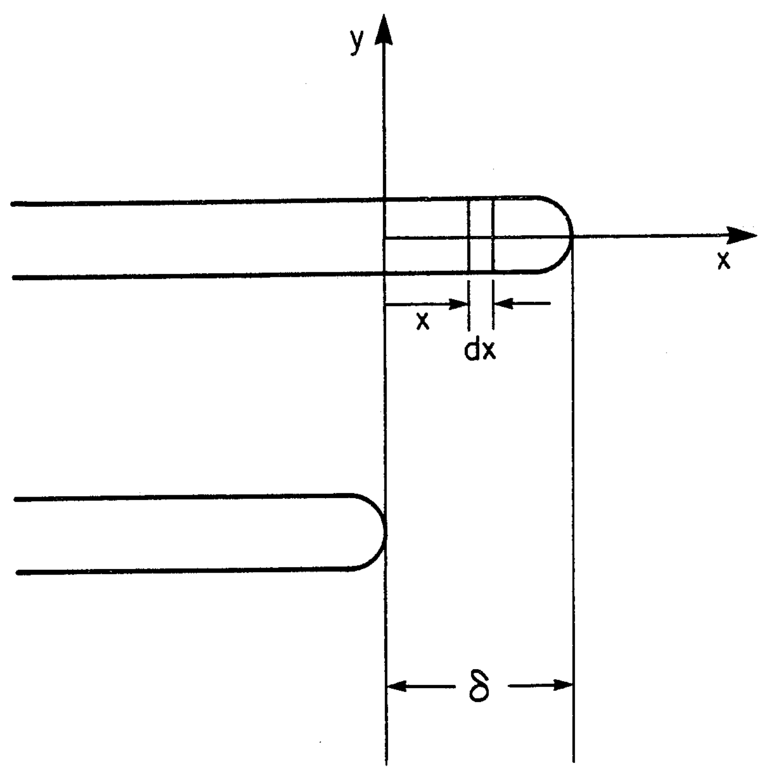

Figure 3. Crack Tip Closure

being moved in the closure process. The divisor of 2 in each term in the integral results from the fact that the stresses which close the crack are zero at the tip and increase moving further along the crack. Hence, the 2 in the denominator is related to the mean stress applied to close the crack. The stresses are evaluated at $r = x$ and $\theta = 0$. The displacements are calculated using $r = \delta - x$ and $\theta = \pi$.

Evaluating the first term of the integral, the stress and displacement terms are those of the Mode I state as found in equations (1.9) and (1.14) respectively. Substituting the values for r and θ:

$$\sigma_y = \frac{K_I}{(2\pi x)^{1/2}} \tag{1.33}$$

$$v = \frac{4K_I(1-\nu^2)}{E} \left[\frac{\delta - x}{2\pi}\right]^{1/2} \tag{1.34}$$

The integral then becomes:

$$G_I = \lim_{\delta \to 0} \frac{2K_I^2(1-\nu^2)}{\delta \pi E} \int_0^\delta \left[\frac{1 - (x/\delta)}{(x/\delta)}\right]^{1/2} dx \tag{1.35}$$

G_I is the Mode I component of the total energy release rate which is:

$$G = G_I + G_{II} + G_{III} \tag{1.36}$$

The substitution of $x/\delta = \sin^2\phi$ in equation (1.35) results in:

$$G_I = \lim_{\delta \to 0} \frac{2K_I^2(1-\nu^2)}{\delta \pi E} \int_0^{\pi/2} \left[\frac{1 - \sin^2\phi}{\sin^2\phi}\right]^{1/2} (2\delta)\sin\phi\cos\phi \, d\phi \tag{1.37}$$

$$= \lim_{\delta \to 0} \frac{4K_I^2(1-\nu^2)}{\pi E} \int_0^{\pi/2} \cos^2\phi \, d\phi \tag{1.38}$$

$$= \lim_{\delta \to 0} \frac{4K_I^2(1-\nu^2)}{\pi E} \left[\frac{\phi}{2} + \frac{\sin 2\phi}{4}\right]_0^{\pi/2} \tag{1.39}$$

$$= \frac{K_I^2(1-\nu^2)}{E} \qquad \text{(Plane Strain)} \tag{1.40}$$

For plane stress:

$$G_I = K_I^2/E \tag{1.41}$$

The evaluation of the second term in the integral expression of equation (1.32) is made using the stress and displacement expressions of equation (1.18) and (1.21) respectively. The calculations are the same as those of G_I except for the presence of K_{II} in the equations instead of K_I. The result is the Mode II component of the energy release rate:

$$G_{II} = \frac{K_{II}^2(1-\nu^2)}{E} \qquad \text{(Plane Strain)} \tag{1.42}$$

or:

$$G_{II} = \frac{K_{II}^2}{E} \qquad \text{(Plane Stress)} \tag{1.43}$$

The third term in the integral expression of equation (1.32) is calculated using equations (1.25) and (1.27) for the

stress and displacement terms respectively. The procedure is the same, with a difference arising in the resultant form of the displacement expression as compared to the previous calculations. In this case:

$$\tau_{yz} = \frac{K_{III}}{(2\pi x)^{1/2}} \tag{1.44}$$

$$w = \frac{2K_{III}(1+\nu)}{E} (2r/\pi)^{1/2} \tag{1.45}$$

The Mode III component of the energy release rate is:

$$G_{III} = \lim_{\delta \to 0} \frac{2K_{III}{}^2(1+\nu)}{\delta \pi E} \int_0^\delta \left[\frac{\delta - x}{x} \right]^{1/2} \tag{1.46}$$

which reduces to:

$$G_{III} = \frac{K_{III}{}^2(1+\nu)}{E} \tag{1.47}$$

The evaluation of equation (1.32) is at this point complete, with G representing the total energy release rate. The Mode I component, G_I, for the plane strain case is the component that is directly applicable to this research effort, and which is utilized in subsequent computations.

1.3 The Stiffness Derivative Development

The stiffness derivative method as outlined by Parks [7] is based upon the relationship between the change in total potential energy of a linear elastic body with a crack, and the change in the element stiffness matrices of the finite element solution of the problem, both of which result from advancement of the crack. The total potential energy expression as it relates to the finite element solution and the stress intensity factor is developed in this work based on work done by Hellen [11] and Parks [7]. Development of the elasticity equations for the finite element solutions involves the use of matrix notation for the variables, as the equations are representative of systems with many degrees of freedom. For example, the finite element solutions of this work employ the two-dimensional, four-node quadrilateral element. The element has two degrees of freedom at each node and its nodal displacement vector is expressed as:

$$\{u\}^{\ell} = (u_1, v_1, u_2, v_2, u_3, v_3, u_4, v_4)^T \tag{1.48}$$

The ℓ denotes that this is the vector for an individual element, and T specifies the transpose of the designated matrix. The total strain vector at a point on the element is:

$$\{\varepsilon\} = \{\varepsilon\}_e + \{\varepsilon\}_o \tag{1.49}$$

in which $\{\varepsilon\}_e$ represents the primary strains which result from mechanical forces, and $\{\varepsilon\}_o$ represents the secondary strains which are due to thermal or residual effects. The stress vector at this point is:

$$\{\sigma\} = [D]\{\varepsilon\}_e = [D](\{\varepsilon\} - \{\varepsilon\}_o) \tag{1.50}$$

In this equation, [D] is a proportionality matrix consisting of elastic constants of Young's modulus E and Poisson's ratio ν. It is a square symmetric matrix, and therefore:

$$[D]^T = [D] \tag{1.51}$$

The total strain vector and the nodal displacement vector are related by means of the [B] matrix, the terms of which are derivatives of the element shape function at the specified point:

$$\{\varepsilon\} = [B]\{u\}\ell \tag{1.52}$$

The expression for the strain energy density at the point of interest is:

$$\Omega = 1/2\{\sigma\}^T\{\varepsilon\}_e = 1/2\{\sigma\}^T(\{\varepsilon\} - \{\varepsilon\}_o) \tag{1.53}$$

From equations (1.50) and (1.51):

$$\{\sigma\}^T = (\{\varepsilon\}^T - \{\varepsilon\}_o^T)[D]^T = (\{\varepsilon\}^T - \{\varepsilon\}_o^T)[D] \tag{1.54}$$

From equation (1.52):

$$\{\varepsilon\}^T = \{u\}^{\ell T}[B]^T \qquad (1.55)$$

Substituting the previous two equations into equation (1.53) results in:

$$\Omega = 1/2(\{u\}^{\ell T}[B]^T - \{\varepsilon\}_o^T)\ [D]\ ([B]\{u\}^{\ell} - \{\varepsilon\}_o) \qquad (1.56)$$

which expands to:

$$\Omega = 1/2\{u\}^{\ell T}[B]^T[D][B]\{u\}^{\ell} - 1/2\{u\}^{\ell T}[B]^T[D]\{\varepsilon\}_o$$
$$- 1/2\{\varepsilon\}_o^T[D][B]\{u\}^{\ell} + 1/2\{\varepsilon\}_o^T[D]\{\varepsilon\}_o \qquad (1.57)$$

The third term of this expression is equal to its transpose, and can therefore be combined with the second term to produce:

$$\Omega = 1/2\{u\}^{\ell T}[B]^T[D][B]\{u\}^{\ell} - \{u\}^{\ell T}[B]^T[D]\{\varepsilon\}_o$$
$$+ 1/2\{\varepsilon\}_o^T[D]\{\varepsilon\}_o \qquad (1.58)$$

The strain energy of the element Ω^{ℓ} is calculated by integrating the strain energy density of the element volume V:

$$\Omega^{\ell} = \int_{\ell} \Omega dV = 1/2\{u\}^{\ell T}\left[\int_{\ell}[B]^T[D][B]dV\right]\{u\}^{\ell}$$
$$- \{u\}^{\ell T}\int_{\ell}[B]^T[D]\{\varepsilon\}_o dV + 1/2\int_{\ell}\{\varepsilon\}_o^T[D]\{\varepsilon\}_o dV \qquad (1.59)$$

The total potential energy of the element is defined as:

$$P^{\ell} = \Omega^{\ell} - \{u\}^{\ell T}\{L\}_e^{\ell} \tag{1.60}$$

where $\{L\}_e^{\ell}$ is the mechanical load vector which causes the primary strains. In addition:

$$\{L\}_o^{\ell} = \int_{\ell}[B]^T[D]\{\varepsilon\}_o dV \tag{1.61}$$

where $\{L\}_o^{\ell}$ is the load vector related to the secondary strains in the element. The element stiffness matrix is defined as:

$$[K]^{\ell} = \int_{\ell}[B]^T[D][B]dV \tag{1.62}$$

and:

$$S^{\ell} = 1/2\int\{\varepsilon\}_o^T[D]\{\varepsilon\}_o dV \tag{1.63}$$

Using equations (1.61) through (1.63), the total potential energy can be rewritten as:

$$P^{\ell} = 1/2\{u\}^{\ell T}[K]\{u\}^{\ell} - \{u\}^{\ell T}\{L\}_o^{\ell} + S^{\ell} - \{u\}^{\ell T}\{L\}_e^{\ell} \tag{1.64}$$

This expression is defined for the overall structural application by deleting the superscripts ℓ designating element application. The total load vector can be written as:

$$\{L\}_T = \{L\}_e + \{L\}_o \tag{1.65}$$

In the overall sense, the load vector $\{L\}_e$ corresponds to loads that are applied externally since the internal forces all cancel

at the internal nodes due to equilibrium considerations [11]. The total potential energy for the overall structure is:

$$P = 1/2\{u\}^T[K]\{u\} - \{u\}^T\{L\}_T + S \tag{1.66}$$

In the current study, the thermal and residual effects are negligible and, therefore,

$$\{L\}_o = S = 0 \tag{1.67}$$

and

$$P = 1/2\{u\}^T[K]\{u\} - \{u\}^T\{L\}_e \tag{1.68}$$

Comparing this relation to the Griffith criterion, the total potential energy P corresponds to the available energy for crack growth. The first term on the right side is the elastic strain energy of the structure, and the second term on the right side is the work done by external forces. Equation (1.68) can be rewritten as:

$$-W = U - F \tag{1.69}$$

where

$$W = -P \tag{1.70}$$

$$U = 1/2\{u\}^T[K]\{u\} \tag{1.71}$$

$$F = \{u\}^T\{L\}_e \tag{1.72}$$

The Griffith criterion expression (equation 1.31) is related to the energy release rate such that [1]:

$$G = \frac{d}{da}(F - U) \tag{1.73}$$

Using the Griffith criterion and equations (1.70) through (1.73), the energy release rate is:

$$\begin{aligned} G = \left[-\frac{\partial P}{\partial a}\right]_{load} &= \frac{\partial\{u\}^T}{\partial a}\{L\}_e + \{u\}^T\frac{\partial\{L\}_e}{\partial a} \\ &- 1/2\,\frac{\partial\{u\}^T}{\partial a}[K]\{u\} - 1/2\,\{u\}^T\frac{\partial[K]}{\partial a}\{u\} \\ &- 1/2\,\{u\}^T[K]\frac{\partial\{u\}}{\partial a} \end{aligned} \tag{1.74}$$

Reducing:

$$- 1/2\,\{u\}^T[K]\frac{\partial\{u\}}{\partial a} = - 1/2\,\frac{\partial\{u\}^T}{\partial a}[K]\{u\} \tag{1.75}$$

which leads to:

$$G = \frac{\partial\{u\}^T}{\partial a}\left[\ \{L\}_e - [K]\{u\}\ \right] + \{u\}^T\ \frac{\partial\{L\}_e}{\partial a}$$

$$- 1/2\ \{u\}^T \frac{\partial[K]}{\partial a}\ \{u\} \qquad (1.76)$$

Since external forces are independent of the change in crack length:

$$\frac{\partial\{L\}_e}{\partial a} = 0 \qquad (1.77)$$

Also:

$$\{L\}_e - [K]\{u\} = 0 \qquad (1.78)$$

As a result of equations (1.77) and (1.78), the energy release rate becomes:

$$G = -\ 1/2\ \{u\}^T \frac{\partial[K]}{\partial a}\ \{u\} \qquad (1.79)$$

Combining equations (1.40) and (1.79):

$$\frac{K_I^{\,2}(1-\nu^2)}{E} = -\ 1/2\ \{u\}^T \frac{\partial[K]}{\partial a}\ \{u\} \qquad (1.80)$$

In order to solve equation (1.80), a finite element model must be constructed for the crack problem. Once the mesh has been created, an initial solution is generated with a crack length, a, and an applied in-plane normal loading corresponding to the Mode I

stress state. The results from this solution are the nodal displacement vector $\{u\}$ and the overall stiffness matrix $[K]_a$ for the applied load case. A second solution is then generated in which a contour of nodal points encompassing the crack tip is selected, and they along with the elements interior to the contour are rigidly advanced ahead of the initial crack tip by a small increment Δa, as shown in Figure 4. There is no applied loading in this solution, and the result is the overall stiffness matrix $[K]_{a+\Delta a}$ for the advanced crack case. With the compiled output from the finite element solutions, the stress intensity factor can be determined by first making the approximation:

$$\frac{\partial[K]}{\partial a} \simeq \frac{[K]_{a+\Delta a} - [K]_a}{\Delta a} = \frac{\Delta[K]}{\Delta a} \tag{1.81}$$

Then, from equation (1.80):

$$K_I = \left[\frac{-E}{2(1-\nu^2)} \{u\}^T \frac{\Delta[K]}{\Delta a} \{u\} \right]^{1/2} \tag{1.82}$$

It is important to note that due to the symmetry of the crack configuration, only the upper half of the crack is actually modeled, as shown in Figure 4. Therefore, the value of the strain energy release rate G obtained from such a finite element solution is half of that expressed in equation (1.79). The latter value is used to calculate K_I in equation (1.82) for the overall crack configuration.

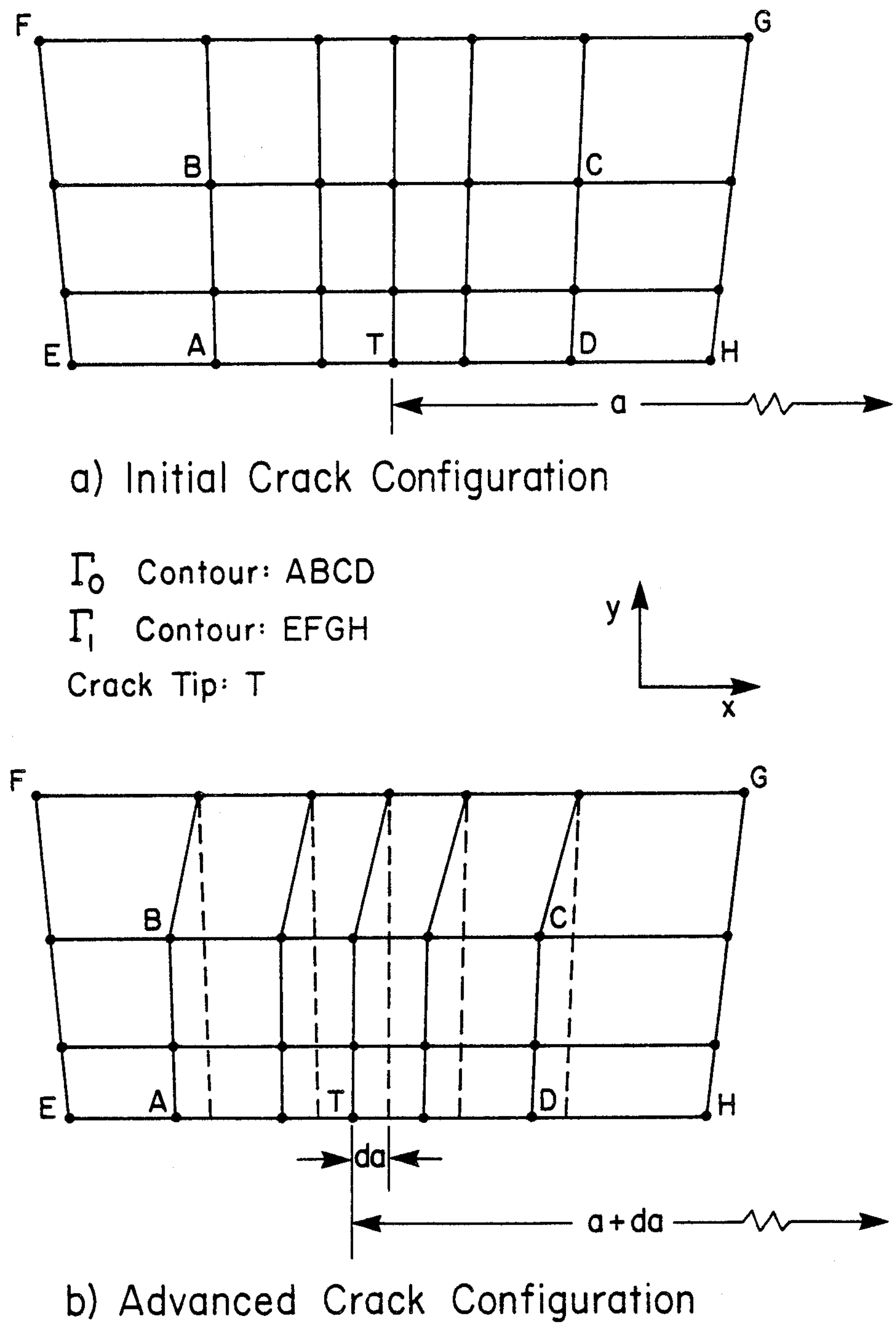

Figure 4. Finite Element Model Crack Tip Advancement

Equation (1.82) essentially provides the same result as that discussed by Parks except for a minor variation. In the solution by Parks, he makes the following approximation [7]:

$$\frac{\partial[K]}{\partial a} = \sum_{i=1}^{N_c} \frac{\partial[k_i{}^c]}{\partial a} \simeq \sum_{i=1}^{N_c} \frac{\Delta[k_i{}^c]}{\Delta a} \tag{1.83}$$

The reason for this version is that when the contour Γ_o is advanced, the only change in stiffness is that of the elements lying between the contour Γ_o and the next larger nodal contour Γ_1 which is also shown in Figure 4. Therefore, equation (1.83) is the summation of the stiffness matrix variations of the elements within contours Γ_o and Γ_1 which are the only elements that are deformed in the process.

The expression in equation (1.81) was used in this study instead of that of Parks in equation (1.83) so as to increase computational efficiency. The drawback of the latter is that in order to solve equation (1.83) the specified element stiffness matrices must be separated out from the overall matrices, the differences computed, and then these element matrix variations incorporated back into the overall matrix so that the rest of the matrix operations can be carried out. By using equation (1.81) instead, $\partial[K]/\partial a$ is calculated directly from the finite element output for the overall stiffness matrices, thereby simplifying the computations considerably.

CHAPTER 2: FINITE ELEMENT MODEL DEVELOPMENT

2.1 Computer Program

The development and implementation of the finite element models for the crack configurations examined in this study, require the use of three separate program packages. The overall process generally involves mesh generation, finite element computation, and subsequent calculation of the stress intensity factor. All computation is performed on a Burroughs B7700 computer.

The first computational step is that of finite element mesh generation which is accomplished utilizing the CADOT computer program developed by Quigley [12]. The program is a computer-aided design package capable of complex finite element mesh design and generation in two and three dimensions. Such a programming capability is considered essential for optimum efficiency.

Once the mesh has been created and compiled, it is then input into the finite element program. The program used in this research effort is SAPV which was developed by Bathe, et al. [13]. The elements which are utilized are the two-dimensional, four-node, plane strain quadrilateral elements. The output which is of

interest here consists of the nodal displacement vectors $\{u\}$ and the overall stiffness matrices [K].

Due to the large amount of data output in the stiffness matrices, the solution of equation (1.82) can be a potentially unwieldy one. To handle this problem, the program MATRIXDP (see Appendix A) was created by the author to carry out the computations using minimum computer storage space and thus maximizing the data handling capabilities. In order to do this, only the upper half of the symmetric banded region of the overall stiffness matrix is read in, with each number correlated to its symmetric location when called for in the matrix calculations. The result is that only a portion of the large overall matrices require space in an array rather than storing the entire overall matrices in a redundant manner. The final output from this program is the computed stress intensity factor from equation (1.82).

It is important to note that all phases of computation previously outlined are performed in double precision. This will be discussed further in the results.

2.2 Mesh Design Criteria

In this research effort, three two-dimensional crack configurations are modeled with finite elements. They are the double edge notch (Figure 5) the single edge notch (Figure 6), and the

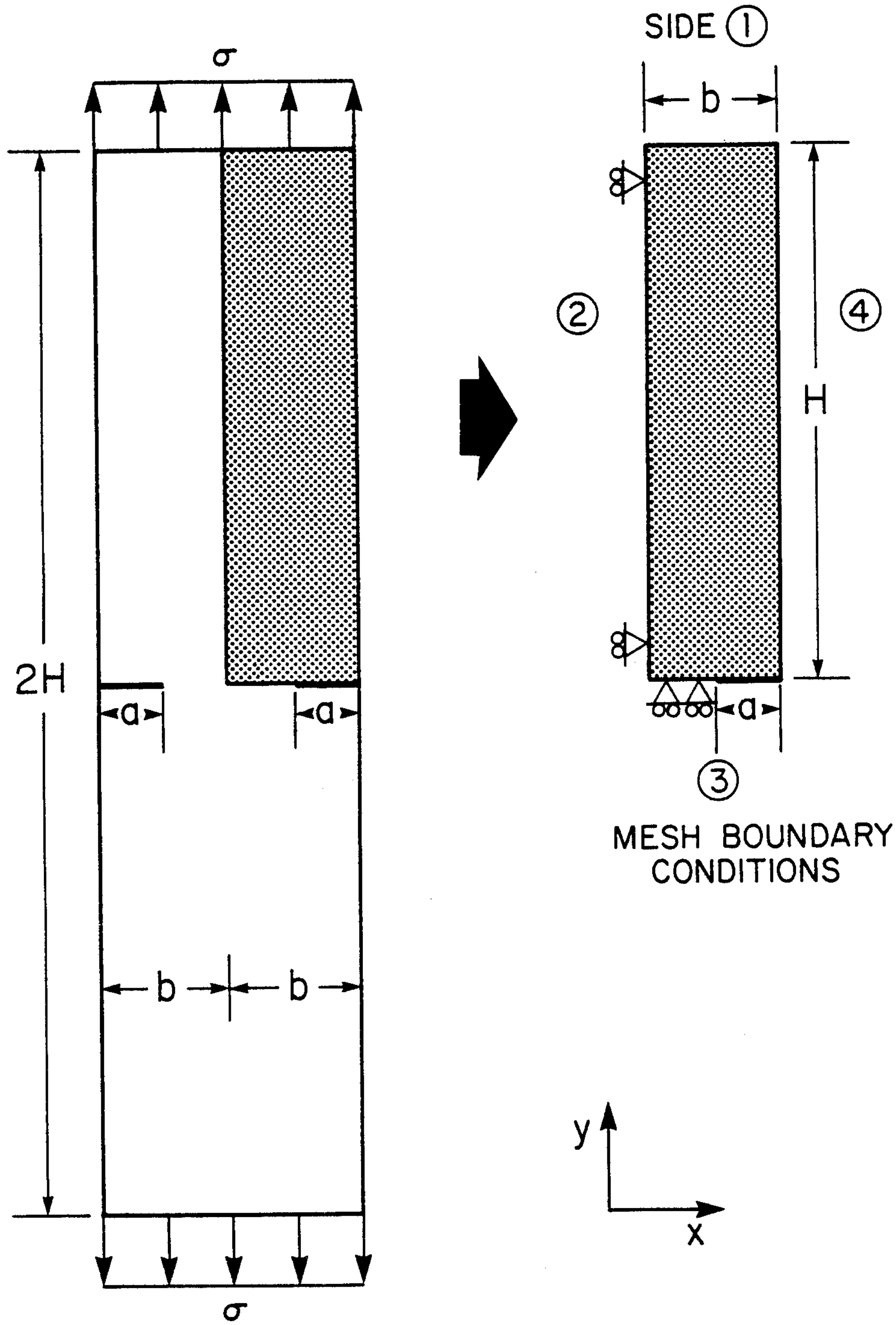

Figure 5. Double Edge Notch Mesh Location and Boundary Conditions

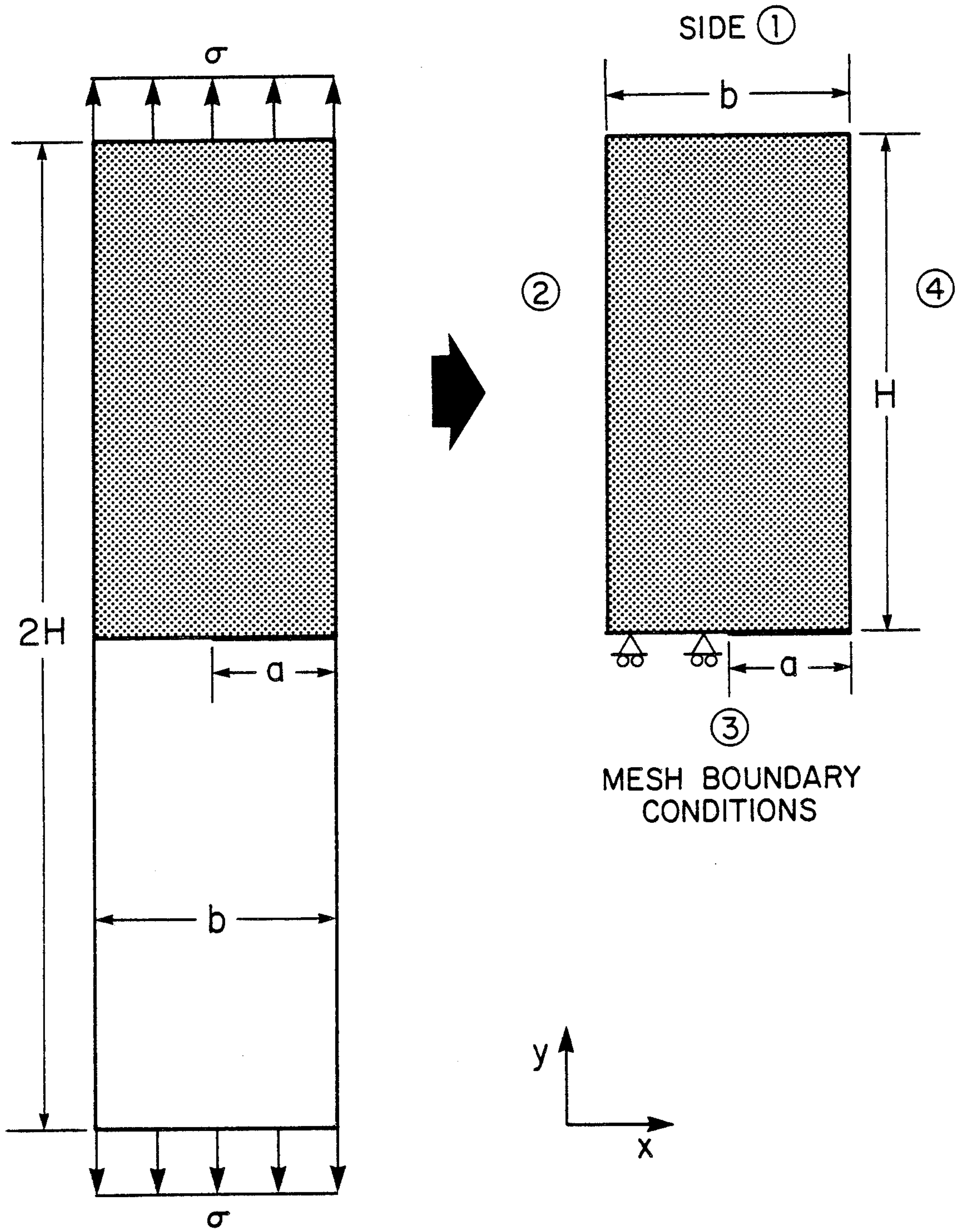

Figure 6. Single Edge Notch Mesh Location and Boundary Conditions

center crack (Figure 7). In all cases the cracks are completely through the plate. The plates are of unit thickness and subject to plane strain conditions.

The most important consideration in the development of the finite element meshes is the optimization of the mesh. To accomplish this, a number of criteria are specified. First, conventional elements are used exclusively throughout the finite element mesh. The reason for such element selection is that, due to the universal availability of the element types used in this study, the method is easily incorporated into most finite element programs currently in use. This is in contrast to methods which utilize specialized singularity elements and are, therefore, not easily transferred to other programs. In addition, the ease of application of the conventional elements as compared to the more specialized elements makes the conventional elements a more natural choice. Specifically, the two-dimensional, four-node quadrilateral element is used in this work. This is in contrast to the model developed by Parks [7] which makes use of triangular and quadrilateral elements. The exclusive use of quadrilaterals is chosen here for reasons of simplicity as well as accuracy. It is easier to generate a mesh of all quadrilaterials than one with a mix of triangles and quadrilaterals. As the problems become more complex, this becomes an increasingly important consideration. In addition, the quadrilateral elements provide a somewhat

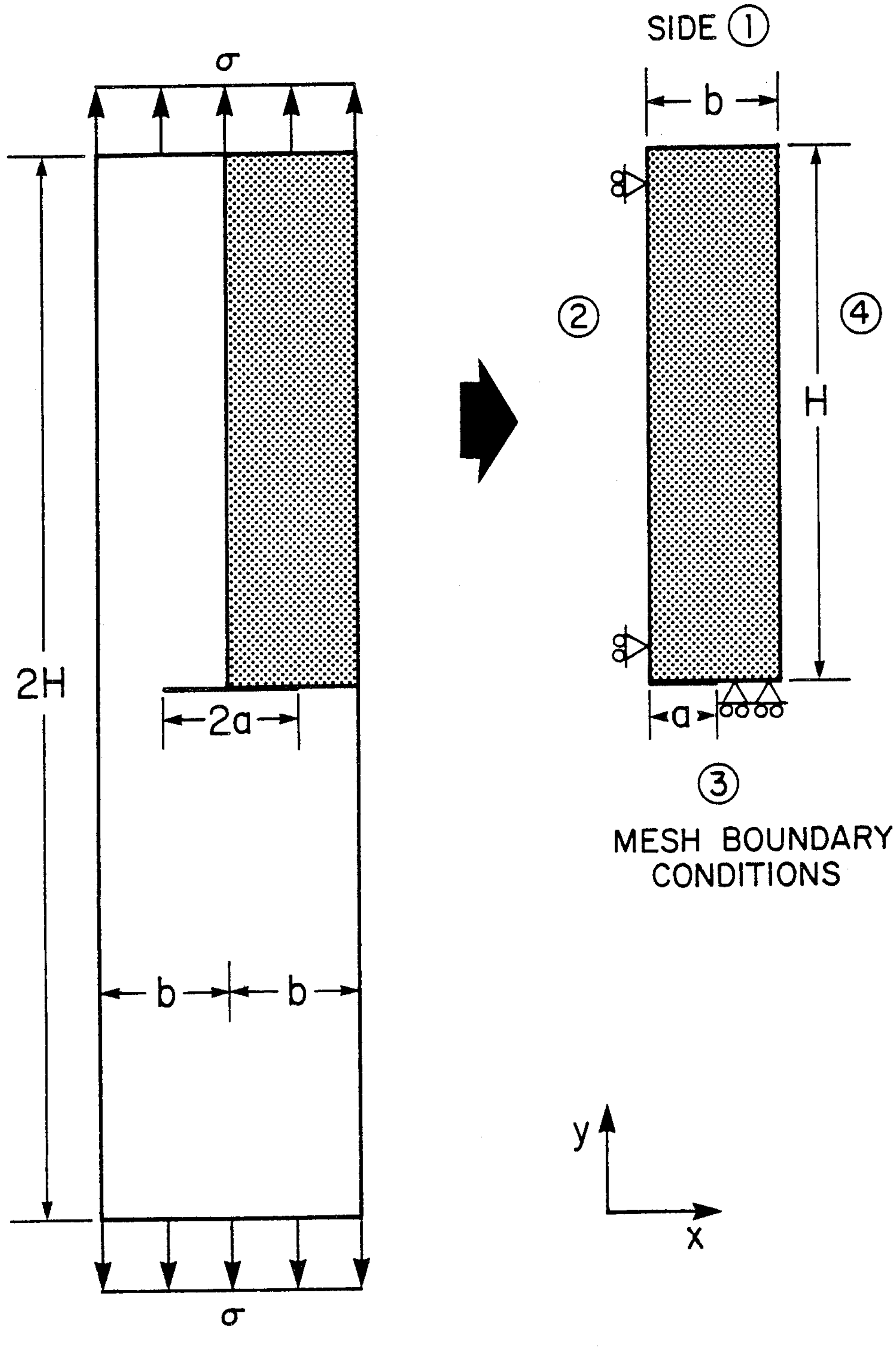

Figure 7. Center Crack Mesh Location and Boundary Conditions

higher degree of accuracy than the triangular elements, and convergence can be achieved with a coarser mesh made up of quadrilaterals [11,14,15].

Another criterion for the mesh optimization is that the mesh should be made as coarse as possible while still achieving the desired accuracy. This is extremely important in view of the fact that while a solution may be theoretically correct, if it requires excessive development and computational time, then it is of little practical use. The accuracy which is sought in the present study is within 5 percent of the analytical solutions for a relatively coarse mesh.

Additionally, the configuration of elements should be such that the mesh can be generated by computer rather than manually specified. Here again, a program such as CADOT [12] is indispensible in the complex problems.

The accuracy of a coarse mesh such as one with the previously discussed characteristics has been found to be very sensitive to the mesh geometry. Based on work done by Guydish and Fleming [8], it can be shown that very good accuracy can be achieved with a properly constructed coarse mesh. They also show that the accuracy of a well-conceived coarse mesh geometry is superior to many ill-conceived fine mesh geometries. Based on these results, the finite element mesh geometries of this current

research were constructed within the following guidelines [8]:

1) The smallest element is at the crack tip with an optimum size of 0.005a.

2) Element size should be increased away from the crack tip by means of a geometric progression for at least one crack length in all directions.

3) The element aspect ratio (Length/Width) should not be more than 50 for individual elements.

2.3 Mesh Configurations

The first crack problem to be modeled is the double edge notch. Due to the symmetry of the problem, it is only necessary to create a mesh for one-fourth of the overall plate. This region is indicated by the shaded area in Figure 5. To account for this symmetry, the appropriate boundary conditions are imposed along the edges as indicated in the figure. The study of this particular crack configuration involved the creation of four different meshes. Their designations are M-2-2, M-2-3, M-2-4, and M-2-7. Each of the four meshes has a different geometry so that the effects of these variations on the solution accuracy can be ascertained.

Mesh M-2-2 can be seen in Figure 8. It has 384 degress of freedom and is composed of 204 nodes and 176 elements. It is a relatively coarse mesh, and one which is easily generated. The smallest element is 0.0254 cm (0.01 inch) on each side and is found at the crack tip. This size is equal to 0.005a as specified in section 2.2. The multiplication factor for the geometric progression of element size away from the crack tip is approximately 3.5 on side 3. The multiplier for sides 2 and 4 is approximately 1.5, and for side 1 it is equal to 1.0. The largest element aspect ratio is approximately 141. This exceeds the ideal maximum of 50 which was previously specified. However, the adverse effect on accuracy is negligible as will be shown in the results. Only two elements have ratios this high, and they are away from the crack tip. The other elements do fall within the specified range.

Mesh M-2-3 is shown in Figure 9. It has 954 degrees of freedom and is composed of 493 nodes and 448 elements. The mesh geometry in the region of the crack is shown in more detail in Figures 10 and 11. It is a more refined mesh than M-2-2, but one which is just as easily generated. The main distinction between the two is that the geometric multiplier for side 3 has been reduced to approximately 1.4 in M-2-3. This results in the finer mesh as illustrated, as well as reducing the largest element aspect ratio to a value of approximately 57.

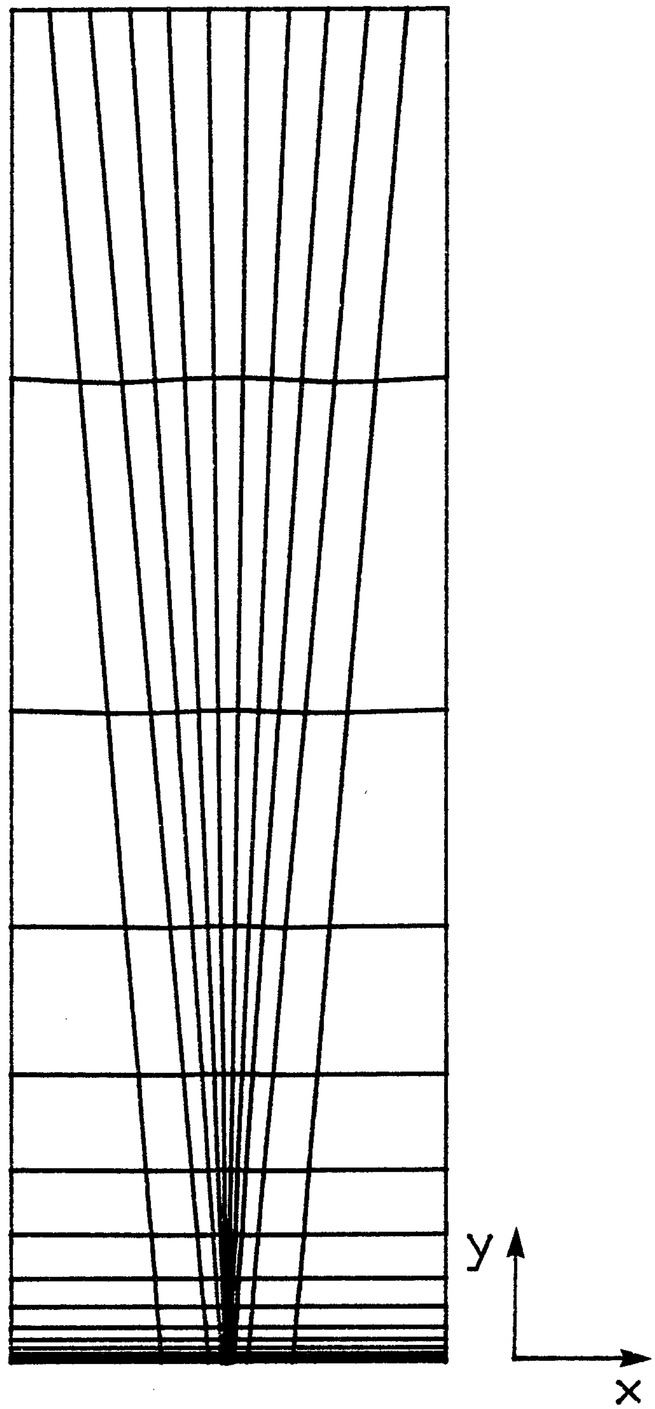

Figure 8. M-2-2 Mesh Geometry

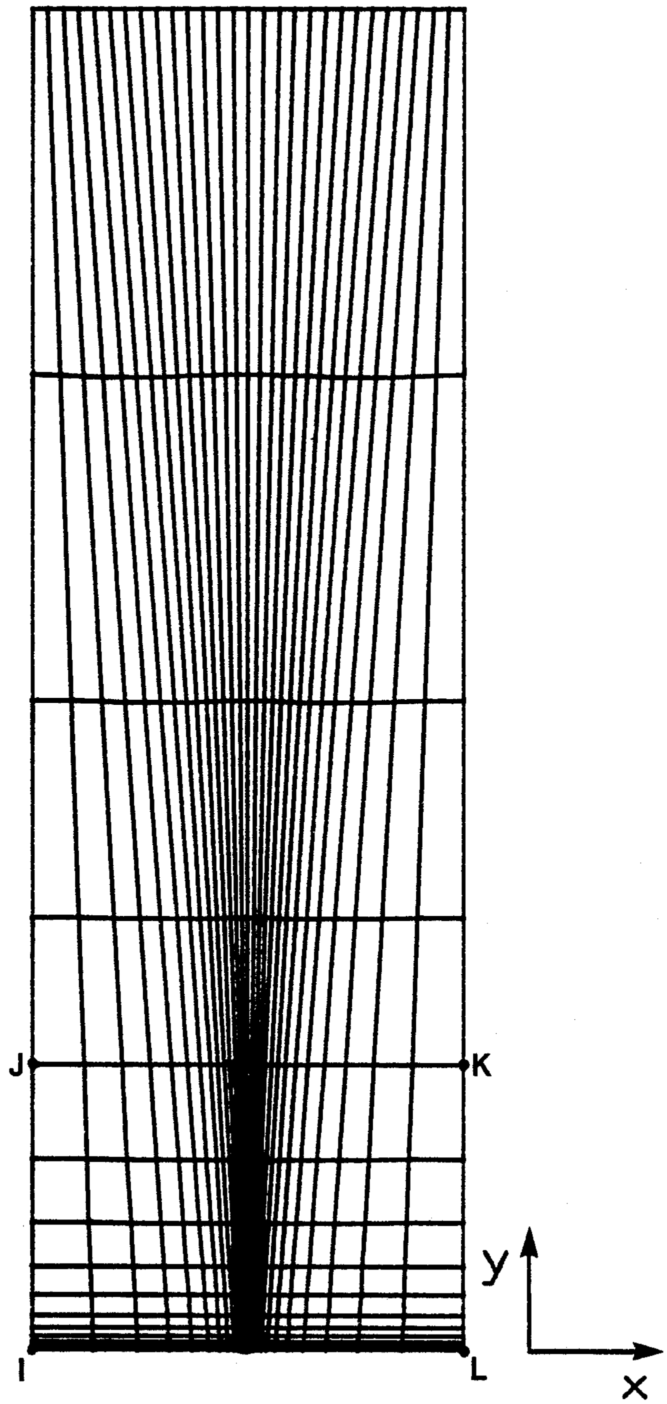

Figure 9. M-2-3 Mesh Geometry

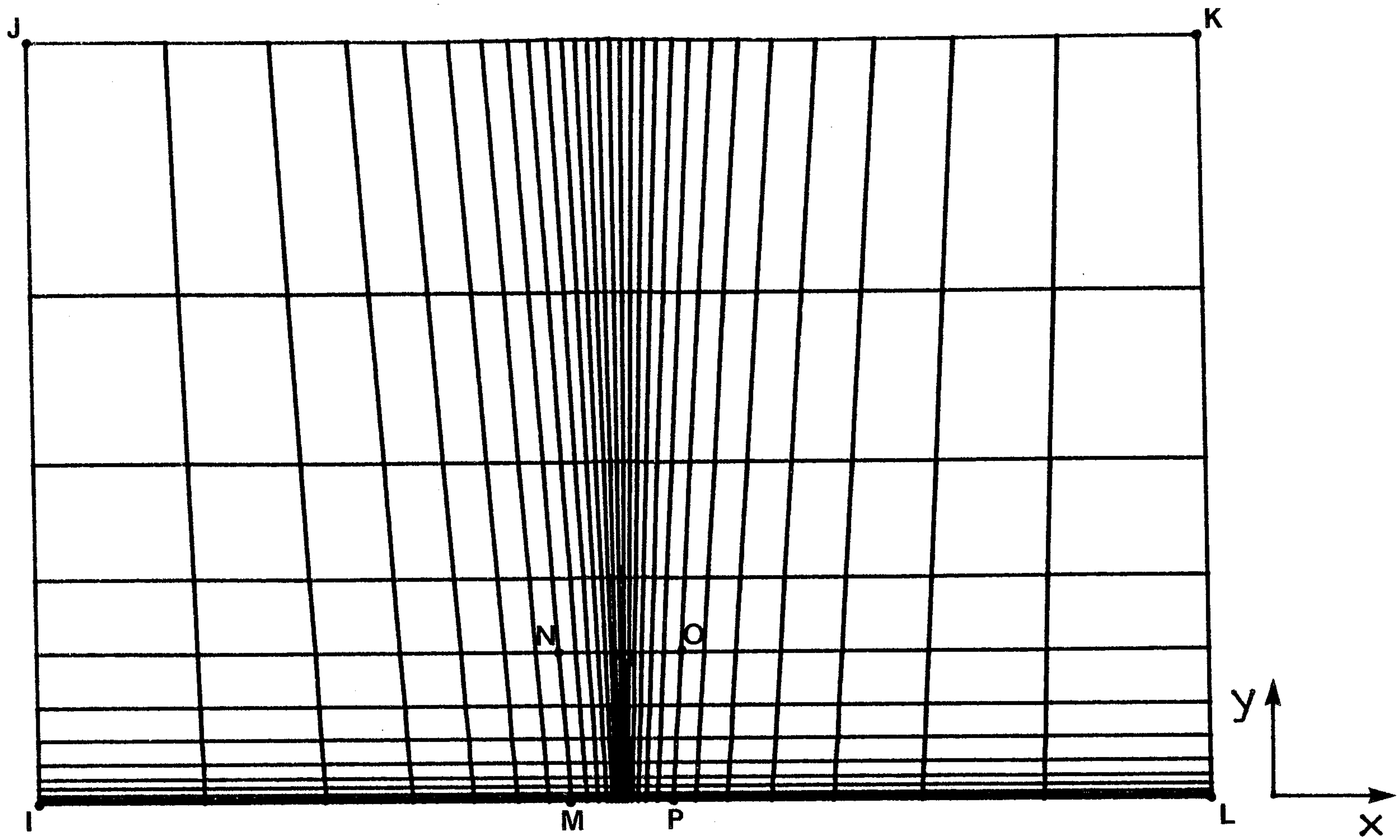

Figure 10. M-2-3 Crack Region Enlarged View

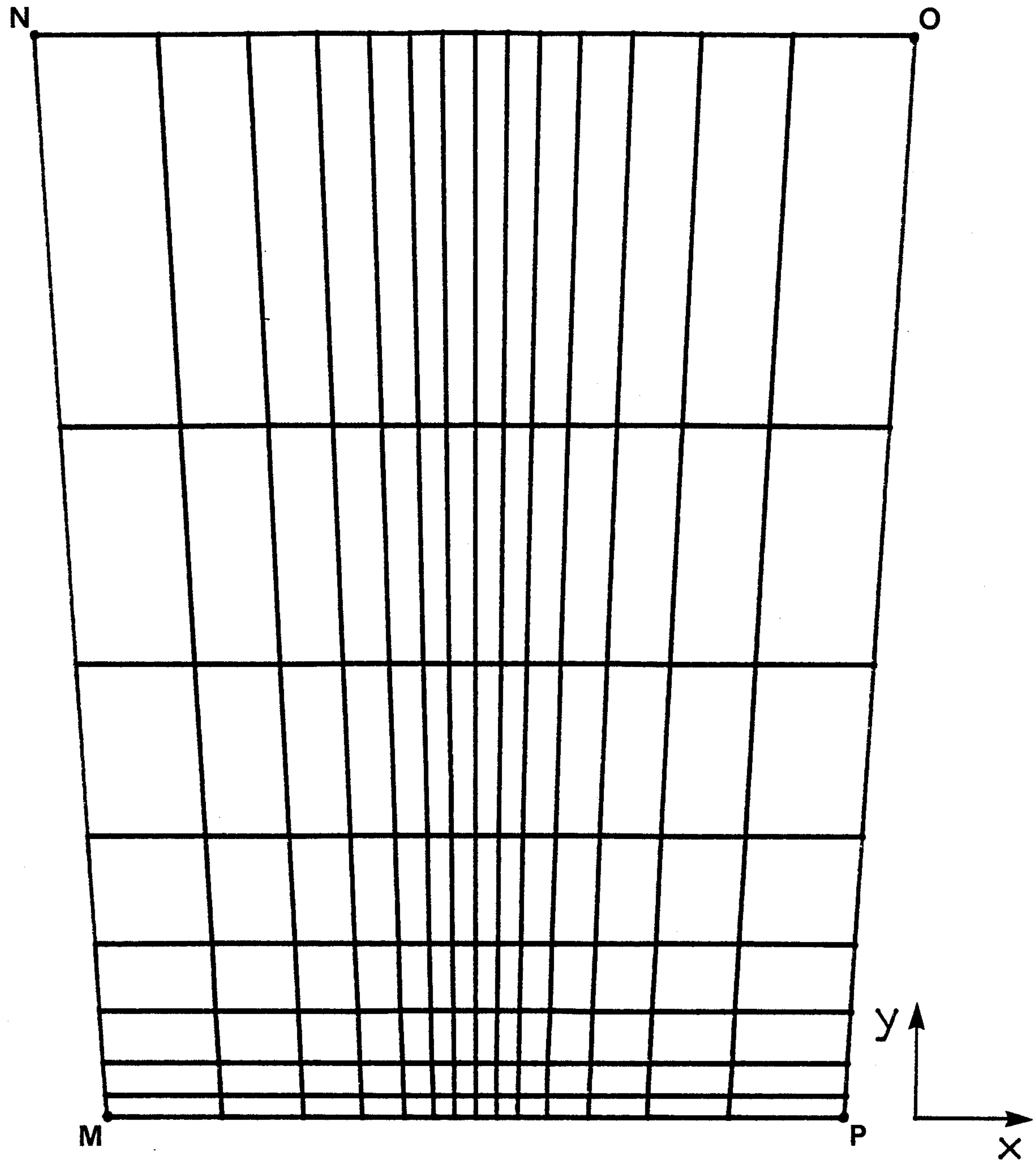

Figure 11. M-2-3 Crack Tip Region Enlarged View

Mesh M-2-4 is a more distinct contrast to the previous two configurations. It is found in Figure 12 and it has 2085 degrees of freedom, along with 1066 nodes and 1000 elements. The largest difference in this case is that it does not employ a geometric progression for increasing the element size away from the notch. Instead, the element size remains constant over extended regions. For the area around the crack tip extending one crack length in the x and y directions the elements are all square with a side dimension of 0.254 cm (0.1 inch). In the area outside this region the elements are all uniform rectangles with width in the x-direction of 0.254 cm (0.1 inch) and length in the y-direction of 5.08 cm (2.0 inch). While this mesh is more refined overall than the previous ones, it is coarser around the crack tip. The elements adjacent to the crack tip measure 0.254 cm (0.1 inch) on each side, equaling 0.05a rather than the optimum 0.005a. The net effect of this versus the increased overall refinement on the solution accuracy is discussed in the results. In this mesh, the largest element aspect ratio is only equal to 20.

Mesh M-2-7 was constructed in an effort to approximate how coarse the mesh could be made without exceeding the specified 5 percent error limit. This mesh is found in Figure 13, and has 162 degrees of freedom, with 88 nodes and 70 elements. For this case, the geometric multiplier is approximately 3.5 for sides 2, 3, and 4. Side 1 again has a multiplier of 1.0. The largest element

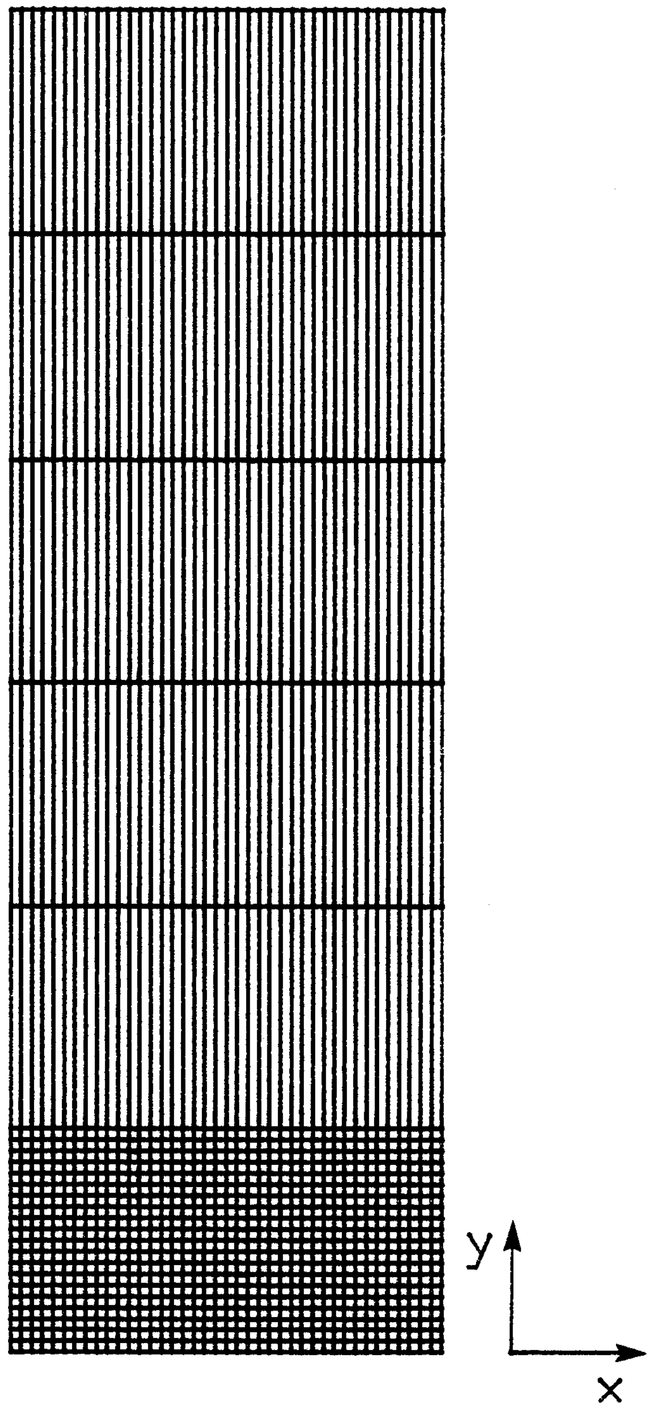

Figure 12. M-2-4 Mesh Geometry

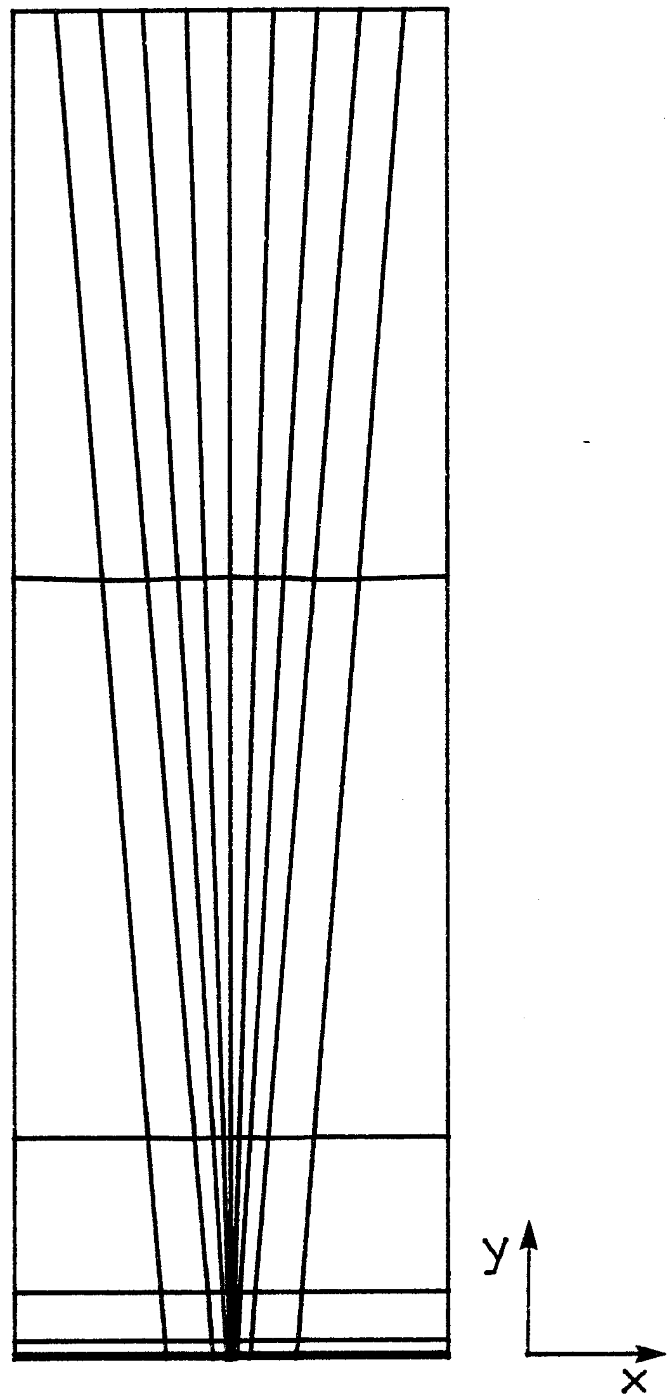

Figure 13. M-2-7 Mesh Geometry

aspect ratio is approximately 140 which is comparable to that of mesh M-2-2.

The single edge notch problem and the center edge crack problem are also modeled in a manner similar to that just discussed for the double edge notch problem. The single edge notch problem is symmetric such that one-half of the plate is meshed as shown in Figure 6. The symmetry of the center crack problem requires that only one-fourth of the plate be meshed as indicated in Figure 7. The same previously developed meshes are also compatible with these two crack geometries. The significant difference is that for each of the three crack geometries, the boundary conditions are different. The boundary conditions for these crack geometries are indicated in Figures 5 through 7.

CHAPTER 3: RESULTS

3.1 Double Edge Notch

3.1.1 Theoretical Solution

The analytical expression for the Mode I stress intensity factor of the double edge notch problem is expressed as [9]:

$$K_I = \sigma(\pi a)^{1/2} f(a/b) \tag{3.1}$$

where the factor, f(a/b), is a function of the crack half-length, a, and the plate half-width, b (see Figure 5). A number of expressions for f(a/b) have been developed in the literature. The one chosen for this study can be found in Reference [9] and is the following:

$$f(a/b) = 1.12 + 0.203(a/b) - 1.197(a/b)^2 + 1.930(a/b)^3 \tag{3.2}$$

This equation was derived by Brown based on a least square fitting to Bowie's results. The assumed accuracy is within 2.0 percent for a/b ratio ≤ 0.7. It should be noted at this point that the theoretical and numerical results for K_I in this chapter are non-dimensionalized in the form $K_I/\sigma a^{1/2}$ for purposes of comparison among varying load cases or crack lengths.

3.1.2 Effect of Crack Advance Increment on Solution Accuracy

A significant variable in the stiffness derivative model is the increment by which the crack is advanced, Δa. Comparison of the approximation made in equation (1.81):

$$\frac{\partial [K]}{\partial a} \simeq \frac{[K]_{a+\Delta a} - [K]_a}{\Delta a} = \frac{\Delta [K]}{\Delta a} \tag{1.81}$$

with the definition of the derivative:

$$\frac{\partial f(c)}{\partial x} = \lim_{h \to 0} \frac{f(c+h) - f(c)}{h} \tag{3.3}$$

indicates that the approximation of equation (1.81) should converge to the exact value as Δa approaches zero in the limit. The actual application in this problem involves specifying a sufficiently small value for Δa in the finite element mesh to provide reasonable accuracy. This was investigated by generating a number of computer solutions of the double edge notch problem with different values of Δa for each one. For all cases, the mesh is M-2-2, the loading is the same, and the inner contour size r/a is kept constant. In the expression r/a, the term r is the approximate radius around the crack tip of the inner contour. The results of these computations are tabulated in Table 1, and presented graphically in Figure 14. With Δa equal to 0.254 cm (0.1 inch), which is the largest increment of crack advance which was tested, the solution is imaginary. This increment produces a change in the stiffness matrix such that the expression within the

Table 1. Variation of Crack Advance for Double Edge Notch

Mesh M-2-2, r/a = 0.254 cm (0.1 in.), σ = 75.8 MPa (11 Ksi)

$$\left[\frac{K_I}{\sigma a^{1/2}}\right]_{\text{theoretical}} = 2.06225$$

Δa (in.)	$K_I/\sigma a^{1/2}$	Percent Error
1×10^{-1}	2.72515×10^{-1} i	---
1×10^{-2}	1.91393	7.192
1×10^{-3}	2.01165	2.454
1×10^{-4}	2.02119	1.991
1×10^{-5}	2.02214	1.945
1×10^{-6}	2.02224	1.940
1×10^{-7}	2.02225	1.940

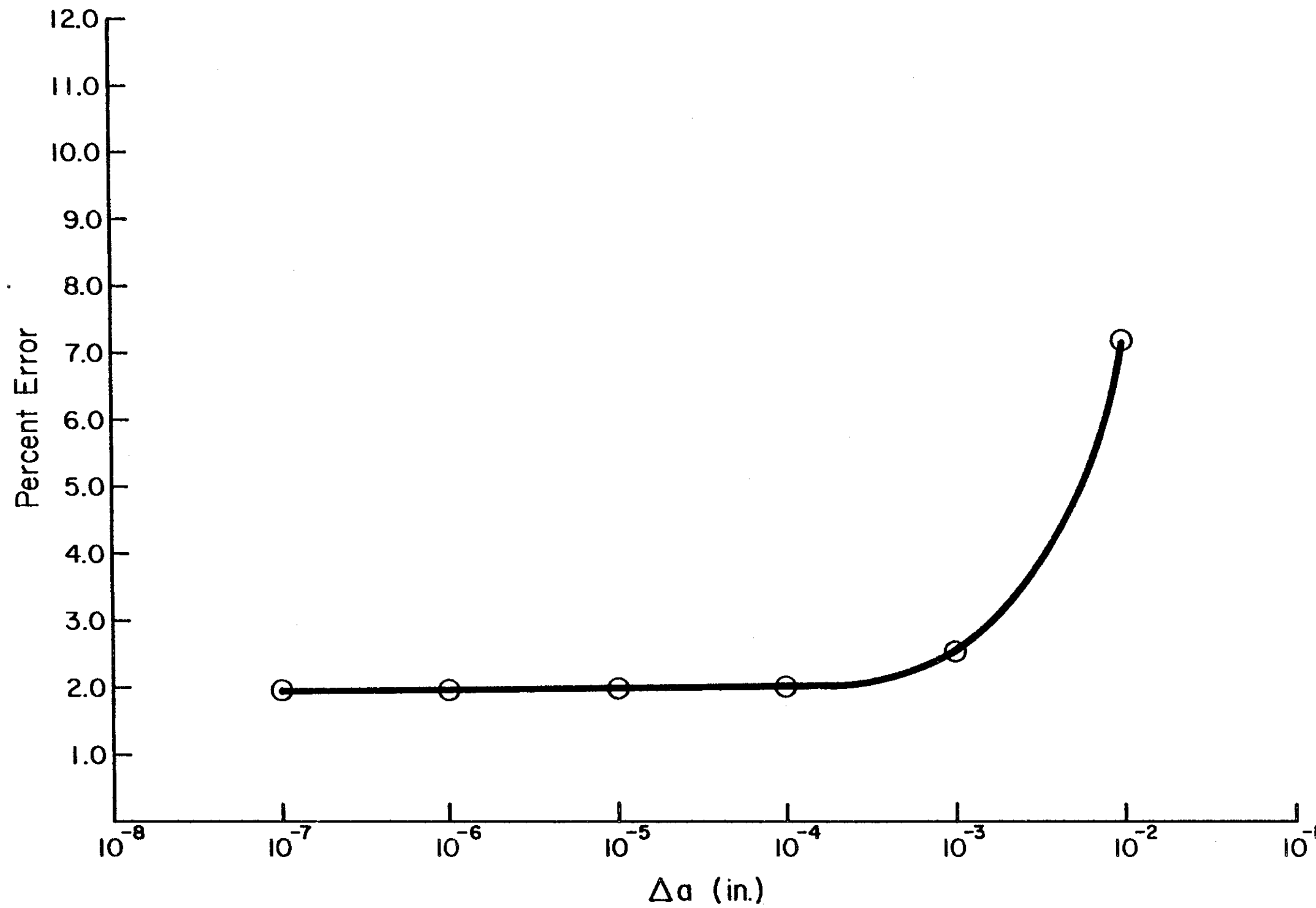

Figure 14. Percent Solution Error vs. Crack Advance Increment (Mesh M-2-2)

square root in equation (1.82) is negative and the solution consequently imaginary and of no use. Decreasing this increment by a factor of ten results in an error of 7.192 percent. By continuing to decrease the increment value, the error continues to decrease correspondingly and approach a value around 1.940 percent for an increment of 2.54×10^{-7} cm (1×10^{-7} inch). At this point, smaller increments of crack tip advancement appear to have insignificant effect upon the accuracy. Therefore, all further computer solutions were produced with 2.54×10^{-7} cm (1×10^{-7} inch) selected as the optimum value for Δa.

3.1.3 Effect of Crack Tip Element Contour Size on Solution Accuracy

A second factor which has an effect on the solution accuracy is the size of the inner contour of elements Γ_o which is specified around the crack tip. This effect was examined by generating another series of computer solutions of the double edge notch problem, again using mesh M-2-2. For this series of computations, the crack advance increment and the loading are kept constant. The results are shown in Table 2. The contour size ratios range from 0. (i.e. the single node at the crack tip) to 0.5 with a corresponding decrease in error from 2.891 percent to 1.553 percent as illustrated in Figure 15.

For the mesh configuration of M-2-2, 0.5 is the maximum

Table 2. Variation of Γ_o Contour Size for Double Edge Notch

Mesh M-2-2, $\Delta a = 2.54 \times 10^{-7}$ cm (1×10^{-7} in.), $\sigma = 75.8$ MPa (11 Ksi)

$$\left[\frac{K_I}{\sigma a^{1/2}}\right]_{theoretical} = 2.06225$$

r/a	$K_I/\sigma a^{1/2}$	Percent Error
0.	2.00264	2.891
0.1	2.02225	1.940
0.3	2.02621	1.748
0.5	2.03022	1.553

Mesh M-2-3, $\Delta a = 2.54 \times 10^{-7}$ cm (1×10^{-7} in.), $\sigma = 72.4$ MPa (10.5 Ksi)

$$\left[\frac{K_I}{\sigma a^{1/2}}\right]_{theoretical} = 2.06225$$

r/a	$K_I/\sigma a^{1/2}$	Percent Error
0.5	2.06131	0.046
0.75	2.06223	0.001

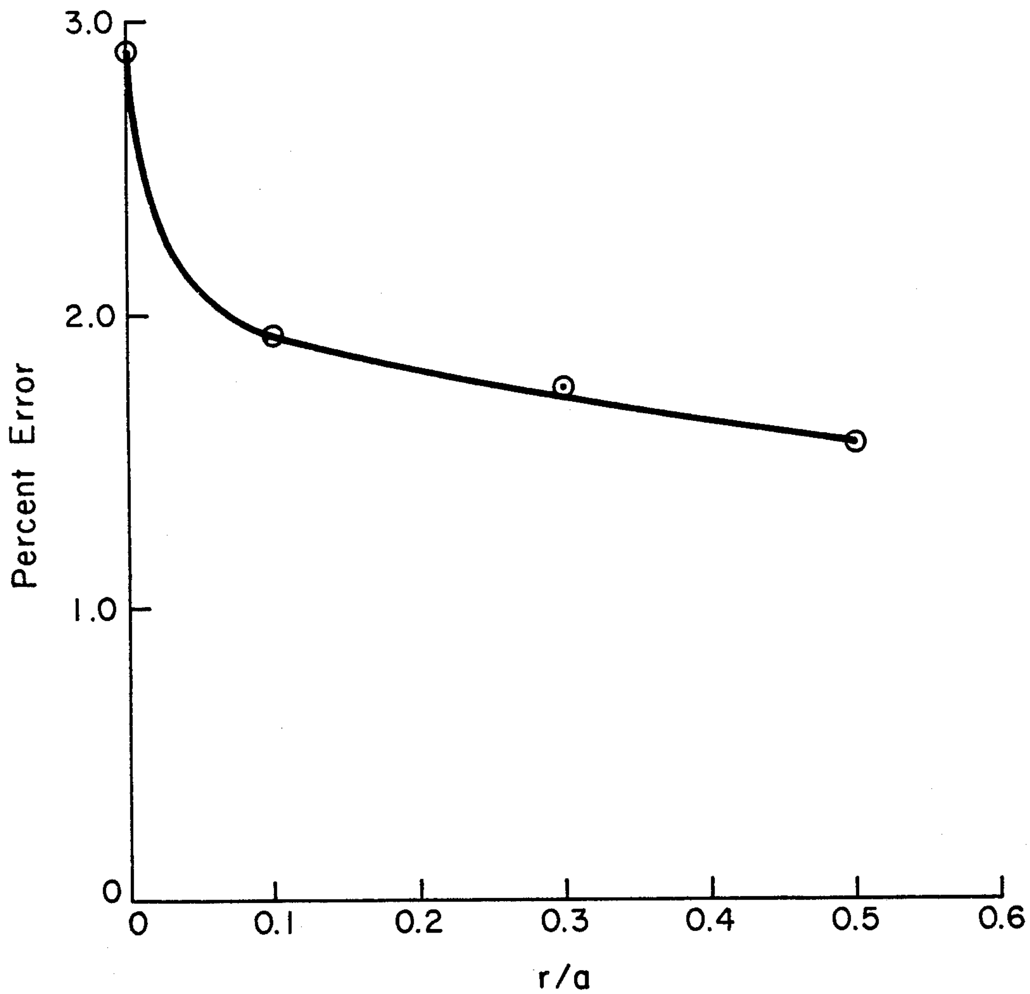

Figure 15. Percent Solution Error vs. Crack Tip Element Contour Size (Mesh M-2-2)

possible size ratio for the inner element contour. The more refined mesh M-2-3 can have a contour size ratio up to 0.75. The results for mesh M-2-3 with inner element contour size ratios of 0.5 and 0.75 are presented in Table 2, with error values of 0.046 percent and 0.001 percent respectively. Again, the same trend is indicated as it is with mesh M-2-2. The results indicate that as the contour size Γ_o increases, the solution accuracy increases correspondingly. Intuitively, this is a logical trend. The region close to the crack tip will show the most significant error between the theoretical and numerical predictions of the stress state due to the presence of the stress singularity at the crack tip. It is, therefore, reasonable to assume that the inner element contour should be of adequate size so as to encompass this region within the rigidly translated elements, with the deformed elements then at a sufficient distance such that the singularity effect is minimized. This assumption is supported by the results.

3.1.4 Effect of Mesh Refinement on Solution Accuracy

A major factor which influences the accuracy of the numerical solution is the mesh geometry. As was discussed in section 2.2, much better accuracy can be achieved with a well-designed coarse mesh than with a fine mesh that has an inefficient geometry. In an effort to demonstrate such effects, a series of computer solutions were generated for the double edge notch

problem for a variety of mesh configurations. The results are tabulated in Table 3. As is indicated, the crack advance increment, and the element contour size are constant throughout. The applied stresses are varied somewhat from case to case but this has no effect on the nondimensionalized solution or its accuracy.

Comparison of meshes M-2-2 and M-2-3, which were discussed in section 2.3, reveals that the latter mesh has essentially the same geometric configuration as the former. The distinction between them is that M-2-3 has approximately 2.5 times the number of elements as does M-2-2. The result is a decrease in error from 1.553 percent to 0.046 percent.

Utilizing the same basic geometric characteristics of mesh M-2-2 in a coarser configuration resulted in mesh M-2-7. The results are that mesh M-2-2 has approximately 2.5 times the number of elements that M-2-7 has, with an error of 1.553 percent for M-2-2, and an error of 5.549 percent for the coarse mesh M-2-7. The results for these three meshes with the same basic geometric configuration are illustrated in Figure 16.

The results indicate that an increase in accuracy can be achieved with mesh refinement if it is handled properly. The judgement to be made in application then becomes a question of how accurate a solution is required weighed against the additional cost of using the more refined mesh. In this specific situation,

Table 3. Mesh Refinement for Double Edge Notch

$\Delta a = 2.54 \times 10^{-7}$ cm (1×10^{-7} in.), $r/a = 0.5$

$$\left[\frac{K_I}{\sigma a^{1/2}} \right]_{\text{theoretical}} = 2.06225$$

Mesh	σ (MPa)	σ (Ksi)	$K_I/\sigma a^{1/2}$	Degrees of Freedom	Percent Error
M-2-2	75.8	11	2.03022	384	1.553
M-2-3	72.4	10.5	2.06131	954	0.046
M-2-4	69	10	1.86797	2085	9.421
M-2-7	69	10	1.94782	162	5.549

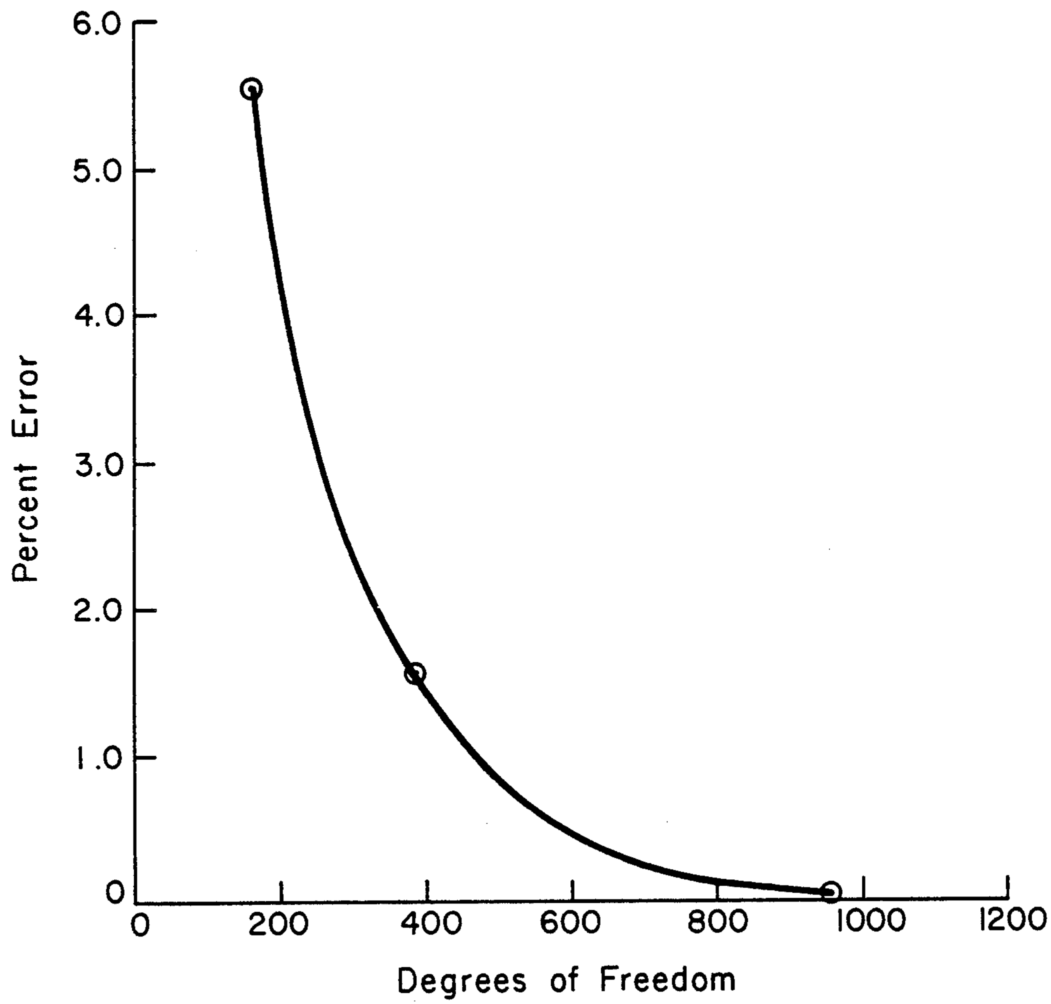

Figure 16. Percent Solution Error vs. Mesh Refinement

mesh M-2-2 is sufficiently accurate in view of the minor additional gain that is made at the expense of more than doubling the mesh size. By contrast, comparison of the results for mesh M-2-4 with the other three cases exemplifies the problems encountered with poorly designed configurations. Despite the fact that M-2-4 has 1000 elements, which is approximately 5.6 times the number of M-2-2, the error went from 1.553 percent for M-2-2 to 9.421 percent for M-2-4. If M-2-4 is examined against the guidelines for mesh optimization in section 2.2, it can be seen that the guidelines are not adhered to. Specifically the size of the elements around the crack tip are too large, and instead of a geometric progression in element size growth away from the crack tip, the elements remain uniform in size. The result is that despite the much denser mesh, the accuracy becomes much worse due to the poor layout, and computational resources are inefficiently utilized.

3.2 Single Edge Notch

3.2.1 Theoretical Solution

For the single edge notch problem, the stress intensity factor is expressed as in equation (3.1). The f(a/b) factor which was chosen is [9]:

$$f(a/b) = 0.265(1 - a/b)^4 + \frac{0.857 + 0.265(a/b)}{(1 - a/b)^{3/2}} \quad (3.4)$$

which was derived by Tada. The assumed accuracy is 0.5 percent for $a/b \geqslant 0.2$.

3.2.2 Numerical Solution

The numerical solution of the single edge notch problem was produced utilizing the optimum parameters which were determined in section 3.1. Mesh M-2-3 is used to model the crack with a crack advance increment of 2.54×10^{-7} cm (1×10^{-7} inch) and an inner element contour size ratio of 0.5. The results are tabulated in Table 4 with a resulting error of 0.858 percent.

3.3 Center Crack

3.3.1 Theoretical Solution

The stress intensity factor for the center crack problem is also expressed as in equation (3.1). The f(a/b) which was chosen is the following [9]:

$$f(a/b) = \left[(2b/\pi a) \tan(\pi a/2b)\right]^{1/2} \quad (3.5)$$

This equation was derived by Irwin and is based on an approximation using a periodic crack solution. The assumed accuracy is within 5 percent for $a/b \leqslant 0.5$.

Table 4. Crack Configuration Results

Mesh M-2-3, $\Delta a = 2.54 \times 10^{-7}$ cm (1×10^{-7} in.), $r/a = 0.5$,

$\sigma = 72.4$ MPa (10.5 Ksi)

Crack Configuration	$K_I/\sigma a^{1/2}$ Theoretical	$K_I/\sigma a^{1/2}$ Numerical	Percent Error
Double edge notch	2.06100	2.06131	0.046
Single edge notch	4.98997	4.94716	0.858
Center crack	2.00000	1.95959	2.021

3.3.2 Numerical Solution

The numerical solution for the center crack problem was also arrived at by employing the optimum parameters from section 3.1. The selected mesh configuration is, therefore, M-2-3 with a crack advance increment of 2.54×10^{-7} cm (1×10^{-7} inch) and an inner element contour size ratio of 0.5. The error for this solution is 2.021 percent. The results are shown in Table 4.

3.4 Sample Computation

A complete output data set from the numerical solution of one of the double edge notch computations has been reproduced in Appendix B. The data corresponds to the solution generated using mesh M-2-7. The input parameters as well as the results are tabulated in Table 3. Specifically, the data is the output from the finite element program, and consists of the overall stiffness matrix for the applied loading configuration, the corresponding nodal displacements, and the overall stiffness matrix for the advanced crack configuration.

The stiffness matrix ouput includes only the upper portion of the symmetric banded region of the actual matrix. From this data, the program MATRIXDP generates the complete set of terms for the matrix calculations as described in section 2.1. In this solution, the stiffness matrix half-bandwidth including the

diagonal term is 20. The stiffness data in Appendix B is read by the program from left to right moving down the page. Reading the data in this fashion, every 20 terms makes up one row of the matrix half-bandwidth. The first of each 20 terms corresponds to the diagonal position for the specified row, and the subsequent terms correspond to consecutive positions to the right of the diagonal term in the array.

The nodal displacement data is arranged with three rows of data for each nonstationary nodal point. The first row, reading from left to right, is comprised of the node number, the x-direction translation, and the y-direction translation. The second row contains the z-direction translation, and the x-direction rotation. The third row is made up of the y-direction rotation and the z-direction rotation. Since the mesh was generated in the y-z plane, only the y and z translations have values, and are the only components of this data used by MATRIXDP to generate the nodal displacement vector.

The data in Appendix B is tabulated as it is read in by the program MATRIXDP. The first data file which is read by the program, consists of the stiffness matrix data for the applied loading case, on pages 71 through 95, and the data for the resulting nodal displacements as found on pages 96 through 99. The stiffness matrix data for the advanced crack case is on pages

100 through 124, and comprises the second data file which is read by the program.

The MATRIXDP program is a user-interactive program. For the data files in Appendix B, the user entries are:

Dimension of Matrix: 162

Half Bandwidth: 20

Number of Nodes (nonstationary): 87

The data is read by the program from stored pack files in the computer system.

An important factor in the numerical solutions of the problems in this study is that it is essential that all computations are performed in double precision. Double precision in this study is 23 significant figures, as shown in Appendix B. This degree of accuracy is necessary in order to generate meaningful results.

CHAPTER 4: CONCLUSIONS

The stiffness derivative finite element technique [7] has been utilized in this study to determine the Mode I stress intensity factors for three crack configurations. The geometries examined included the double edge notch, the single edge notch, and the center crack. The primary guidelines in developing the finite element models were:

1) To use standard, universally available elements throughout the finite element mesh including those at the crack tip.

2) Optimize the finite element mesh geometry for automatic generation by the computer.

3) Construct the finite element mesh as coarse as possible while maintaining the required accuracy.

4) Determine the computational requirements of the "Stiffness Derivative Method," and verify the method's accuracy compared to established analytical solutions.

The results indicate that, following the specified guidelines using the "Stiffness Derivative Method," it is possible to achieve a high degree of accuracy with an optimized, relatively coarse finite element mesh composed of standard, four-node, plane strain, quadrilateral elements.

The design of the mesh configuration was found to have considerable influence on the accuracy of the solutions generated. For a well conceived mesh design with degrees of freedom ranging from 162 to 954, the error ranged from 5.549 percent to 0.001 percent respectively for the double edge notch. In contrast, a mesh designed with less optimization of the geometric configuration and 2085 degrees of freedom, had an error of 9.421 percent. The results for this mesh design resulted in a waste of computing resources and insufficient solution accuracy. Therefore, considerable savings in computing time along with a high degree of accuracy can be realized with a well developed mesh design.

In addition, certain parameters involved in the application of the "Stiffness Derivative Method" were also optimized to maximize the solution accuracy. One important parameter is the size of the increment of crack advance which is specified. The trend that was established is that the increment should be minimized in order to increase the solution accuracy. This was demonstrated for the double edge notch problem in which the

increment was decreased from 10^{-2} in. to 10^{-7} in. with a corresponding decrease in error of 7.192 percent to 1.940 percent respectively.

The second parameter examined for its effect on the solution accuracy was the size of the element contour Γ_o encompassing the crack tip. The results indicated that increasing the radius of this contour, increases the solution accuracy. For the double edge notch problem, an increase in the element contour size ratio, r/a, from 0 to 0.5 reduced the error from 2.891 percent to 1.553 percent.

In summary, the "Stiffness Derivative Method" has been employed in the finite element models of selected crack configurations, and has been found to be fully compatible with the standard four-node quadrilateral element which is typical of most finite element programs. The mesh design which produced the highest accuracy was found to be relatively easy to generate, and utilizing the same basic geometry, the mesh can be refined to produce the desired degree of solution accuracy within reasonable computational time limitations. The results of this study are within acceptable error limits with a relatively coarse mesh. In addition, the implementation of the method is significantly simpler than other methods which require specialized singularity elements, extrapolation of data from numerous generated solutions,

or changing boundary conditions at the crack tip.

Based on these favorable conclusions for the two-dimensional crack configuration, the next logical step is that of a three-dimensional crack configuration such as the penny-crack. The application should differ in certain respects such as the element type and the method of calculation of the stress intensity factor, which will vary along the crack front. The three-dimensional geometry is also a more complex problem computationally. For this reason, the results of this study related to the optimization of the method and computational efficiency, are significant in the development of an accurate and computationally feasible three-dimensional model.

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APPENDIX A

MATRIXDP PROGRAM LISTING

```
$RESET FREE
$SET SUPRS LIMIT=100 LINEINFO
FILE  2(KIND=PACK,MAXRECSIZE=14,BLOCKSIZE=420)
FILE  3(KIND=PACK,MAXRECSIZE=23,TITLE='MATOUT',PROTECTION=SAVE)
FILE  5(KIND=REMOTE)
FILE  6(KIND=REMOTE)
      DOUBLE PRECISION DELK(60000),AK(60000),BK(60000),U(2500)
      DOUBLE PRECISION PROD1(2500),SIGL
      DOUBLE PRECISION XTRAN,YTRAN,ZTRAN,XROT,YROT,ZROT,DPOT,CPOT,TDPOT
      DIMENSION ANS(12)
      INTEGER A,B,C,D,S,HBAND,E,F,G,H,P,Q
      LOGICAL L,ISCS
      DATA IDOT/6H.     /
      DPOT=0.0D0
      E=0
      IBINFL=2
      ISCS=.TRUE.
      WRITE(6,2000)
   10 WRITE(6,2010)
      READ(5,2020) (ANS(I),I=1,11)
      ANS(12)=IDOT
      CHANGE(IBINFL,TITLE=ANS)
      INQUIRE(IBINFL,PRESENT=L)
      IF (L) GO TO 20
      WRITE(6,2030) (ANS(I),I=1,11)
      GO TO 10
   20 E=E+1
      P=1
      Q=2
      KK=0
      WRITE(6,2045)
 2045 FORMAT(/," <ENTER> DIMENSION OF MATRIX",/,11X,
     +          " HALF BANDWIDTH",/,11X,
     +          " NUMBER OF NODES (NONSTATIONARY)")
      READ(5,/) M,HBAND,NODEN
      N=HBAND*M
      F=HBAND/2
      G=HBAND-(F*2)
   25 IF(F.LT.1) GO TO 33
      DO 30 H=1,F
      IF(E.EQ.1) GO TO 27
      READ(2,2050) (BK(I),I=P,Q)
      READ(2,2055) DBK,DDBK
      GO TO 29
   27 READ(2,2050) (AK(I),I=P,Q)
      READ(2,2055) DAK,DDAK
   29 P=P+2
      Q=Q+2
   30 CONTINUE
   33 Q=P+G-1
      IF(P.GT.Q) GO TO 37
      IF(E.EQ.1) GO TO 35
      READ(2,2060) (BK(I),I=P,Q)
      READ(2,2055) DBK,DDBK
      GO TO 37
   35 READ(2,2060) (AK(I),I=P,Q)
      READ(2,2055) DAK,DDAK
   37 P=Q+1
      Q=P+1
      IF (I.LT.N) GO TO 25
      IF (E.GE.2) GO TO 100
      DO 50 II=1,NODEN
      READ(2,2070) NNUM,XTRAN,YTRAN
      READ(2,2072) ZTRAN,XROT
      READ(2,2074) YROT,ZROT
      READ(2,2055) DUM1,DUM2
```

```
      IF (YTRAN.EQ.O.) GO TO 40
      KK=KK+1
      U(KK)=YTRAN
   40 IF(ZTRAN.EQ.O.) GO TO 50
      KK=KK+1
      U(KK)=ZTRAN
   50 CONTINUE
      CLOSE 2
      GO TO 10
  100 CLOSE 2
      DO 500 S=1,N
      DELK(S)=BK(S)-AK(S)
  500 CONTINUE
      DO 700 I=1,M
      WRITE(3,510) I
  510 FORMAT(" I=",I5)
      D=I+HBAND-1
      DO 600 J=I,D
      A=((I-1)*HBAND+J-I+1)
      IF (J.GT.I) GO TO 580
      PROD1(I)=DELK(A)*U(J)
  525 B=I-1
      IF (B.LT.1) GO TO 600
      C=I-HBAND+1
      IF (C.LT.1) C=1
      DO 570 ISYM=C,B
      ASYM=((ISYM-1)*HBAND+I-ISYM+1)
      PROD1(I)=PROD1(I)+DELK(ASYM)*U(ISYM)
  570 CONTINUE
      GO TO 600
  580 PROD1(I)=PROD1(I)+DELK(A)*U(J)
  600 CONTINUE
      DPOT=DPOT+(U(I)*PROD1(I))
      CPOT=U(I)*PROD1(I)
      WRITE(3,650) CPOT
  650 FORMAT(" CPOT=",1PE16.7)
  700 CONTINUE
      TDPOT=(-DPOT/2.0D0)
      SIGL=DSQRT(-DPOT*1.5D7/(9.1D-1*1.0D-7))/2.0D4
      WRITE(6,2080) TDPOT
      WRITE(6,2085) SIGL
 2000 FORMAT(/," STIFFNESS DATA INPUT ROUTINE")
 2010 FORMAT("    <ENTER>INPUT FILENAME")
 2020 FORMAT(11A6)
 2030 FORMAT(/"***ERROR: FILE IS NOT PRESENT ON PACK"
     */"FILE ",11A6)
 2050 FORMAT(2D30.23)
 2055 FORMAT(2F10.0)
 2060 FORMAT(2D30.23)
 2070 FORMAT(F6.0,2D30.23)
 2072 FORMAT(D36.23,D30.23)
 2074 FORMAT(D36.23,D30.23)
 2080 FORMAT(//," POTENTIAL ENERGY CHANGE = ",1PD30.23)
 2085 FORMAT(//," K/(SIG*SQRTA) = ",1PD30.23)
      STOP
      END
```

APPENDIX B

M-2-7 DATA TABULATION

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-.53730768362945902362102D+09	.14671235572042014081278D+07
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O.	O.
O.	O.
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